NATIONAL ACCELERATOR LABORATORY

LARP

Upgrading the LHC Synchrotron-Light Monitors

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LARP CM12
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Synchrotron Light from the LHC

- Protons? Lead ions? Is there sufficient light?
- Where are dipoles with good access?
  - Need a high field: Can’t use a warm magnet.
  - Can’t extract light from arc dipoles: Enclosed in cryostats.
  - Available superconducting dipoles next to drift space:
    - D2 separation dipoles: both sides of ATLAS (IR1) or CMS (IR5).
      - 2.65 T at 7 TeV, 9.45 m long, 1.07 mrad bending angle.
    - D3 separation dipoles: both sides of the RF cavities (IR4).
      - 3.9 T at 7 TeV, 9.45 m long, 1.6 mrad bending angle.
  - D3 bends were chosen.

Beam Size and Critical Wavelength

Beam Energy	**Beam Size**			**Critical Wavelength in Dipole**
	Horizontal	**Vertical**	**Longitudinal**	
(TeV)	(mm RMS)	(mm RMS)	(mm RMS)	(μm)
0.45 (Injection)	1.12	1.48	130	227
2 (Mid-Ramp)	0.53	0.70		2.592
7 (Collisions)	0.28	0.38	77	0.0605

Number of protons:

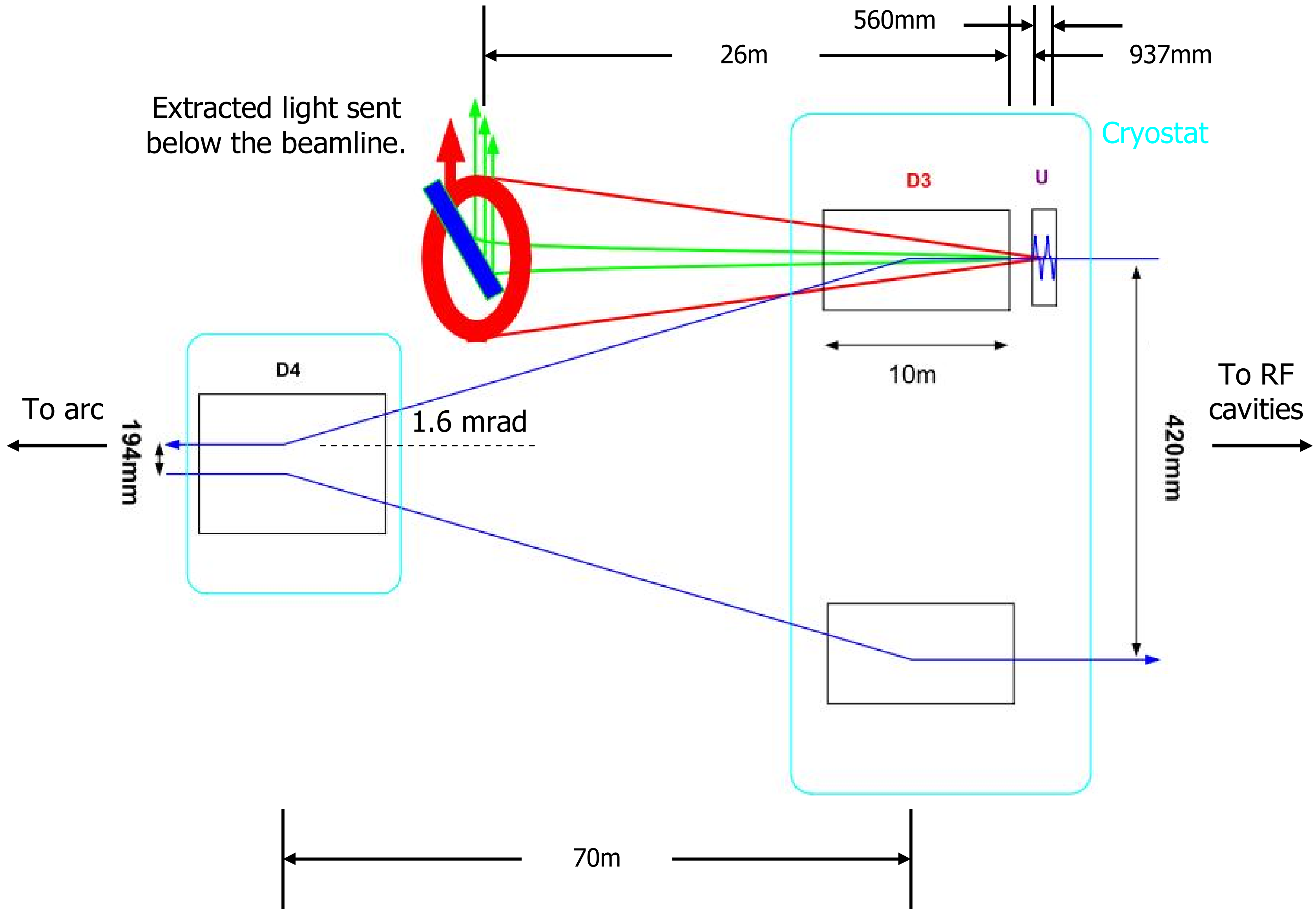
Pilot bunch: 1 bunch of 5×10^9

Full ring: 2808 bunches of $1.2 \times 10^{11} = 3.4 \times 10^{14}$

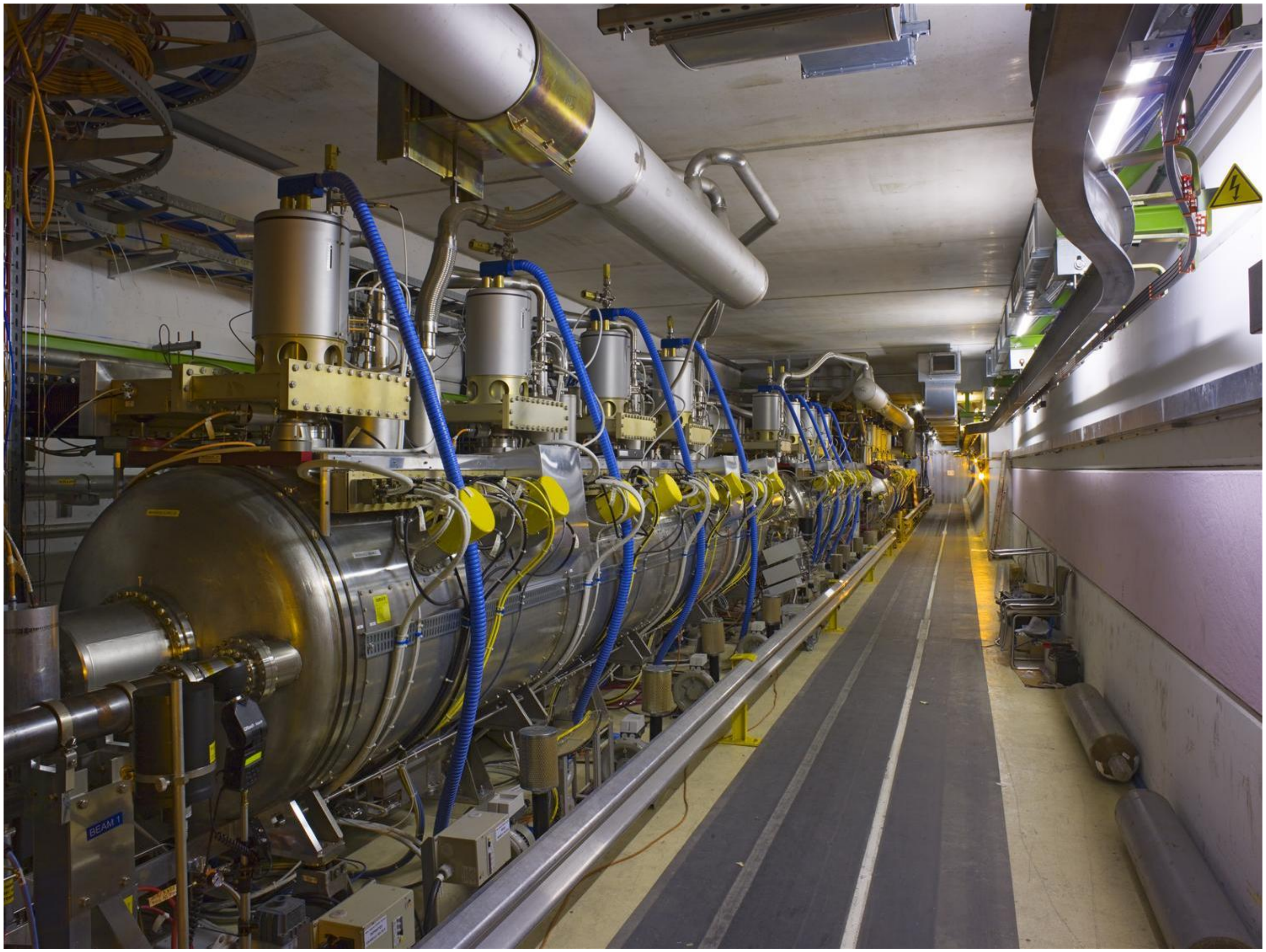
Injection and Ramp

- Measure during the ramp from injection (450 GeV) to collision (7 TeV).
  - Dipole radiation is not sufficient below 2 TeV.
- Add a superconducting 2-period undulator next to the D3 dipole.
  - 5 T, two 28-cm periods.
  - Place upstream of D3, in the same cryostat.
  - Below 1 TeV, light is mainly from undulator.
  - Above 2 TeV, light is from D3.

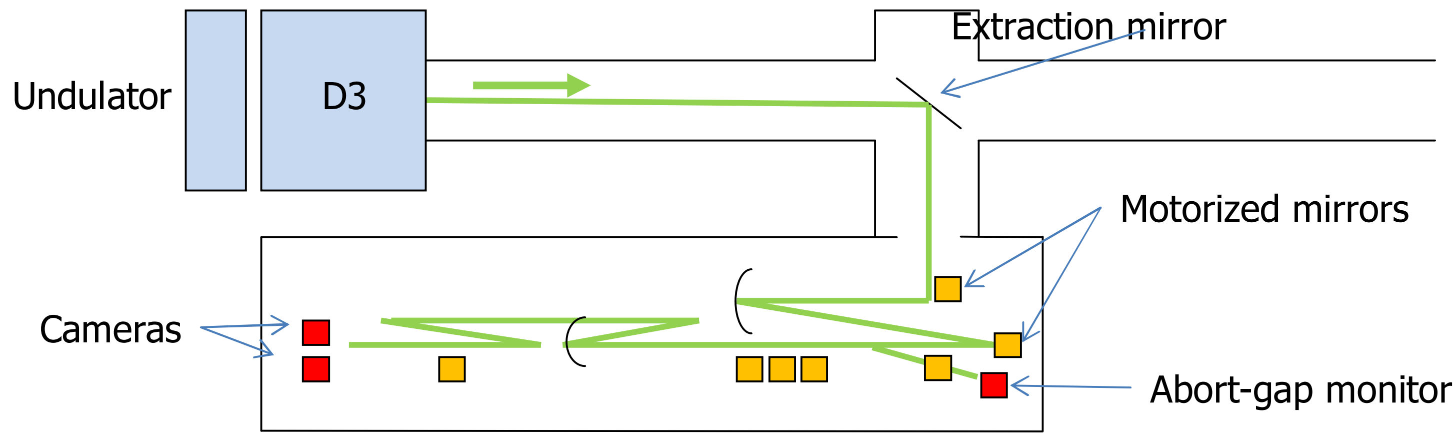
Sketch of SLM Sources



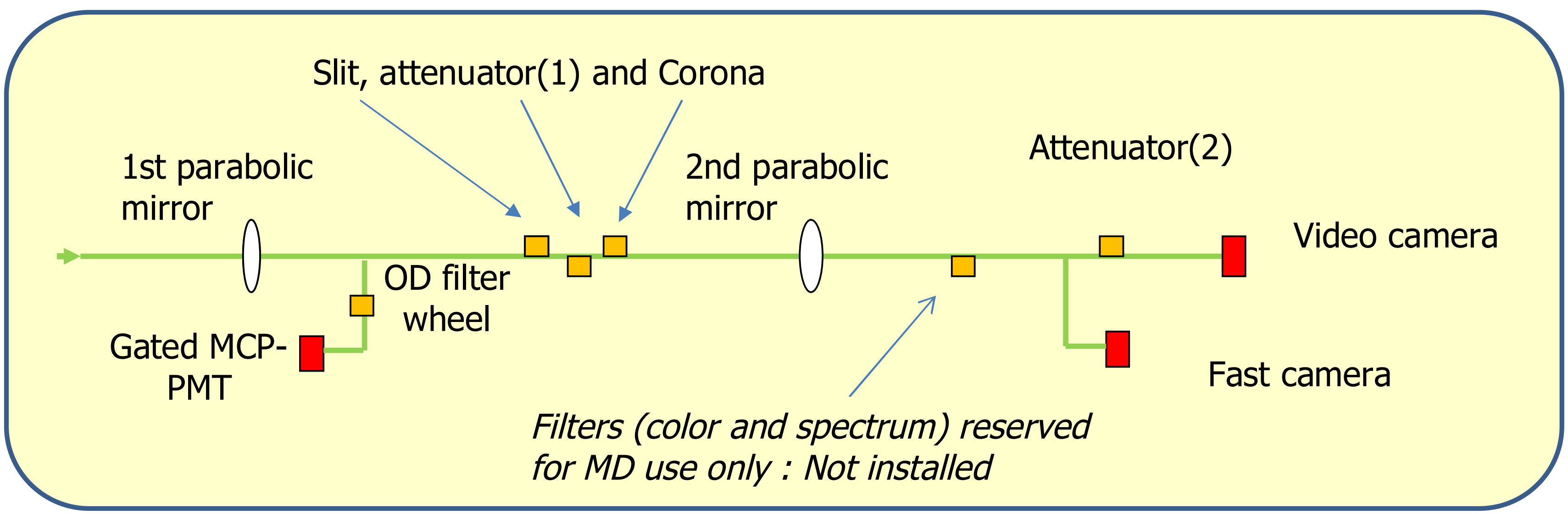
RF Cavities



Present Optical Layout



Optics, Unfolded

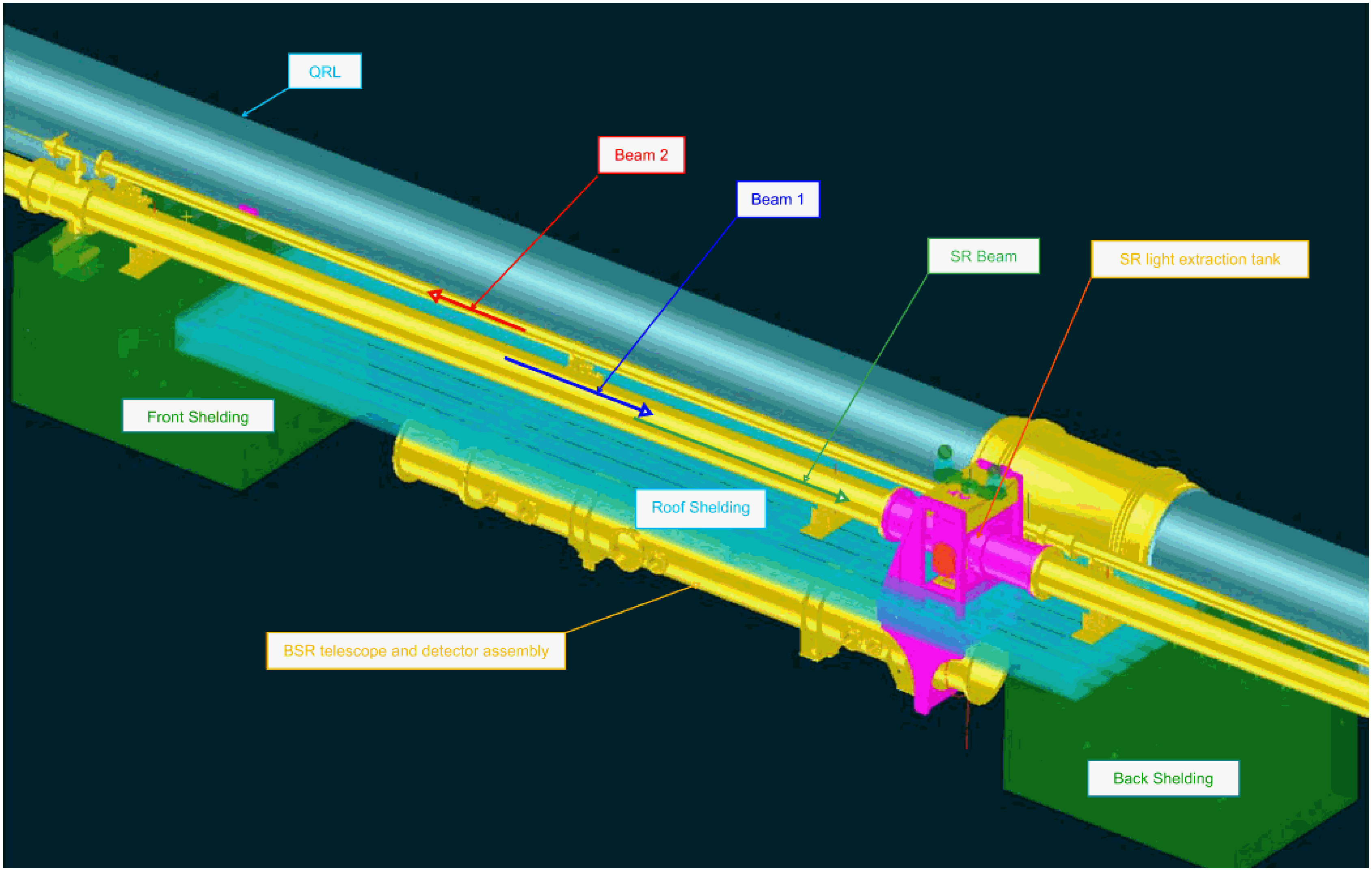


Thibaut Lefevre

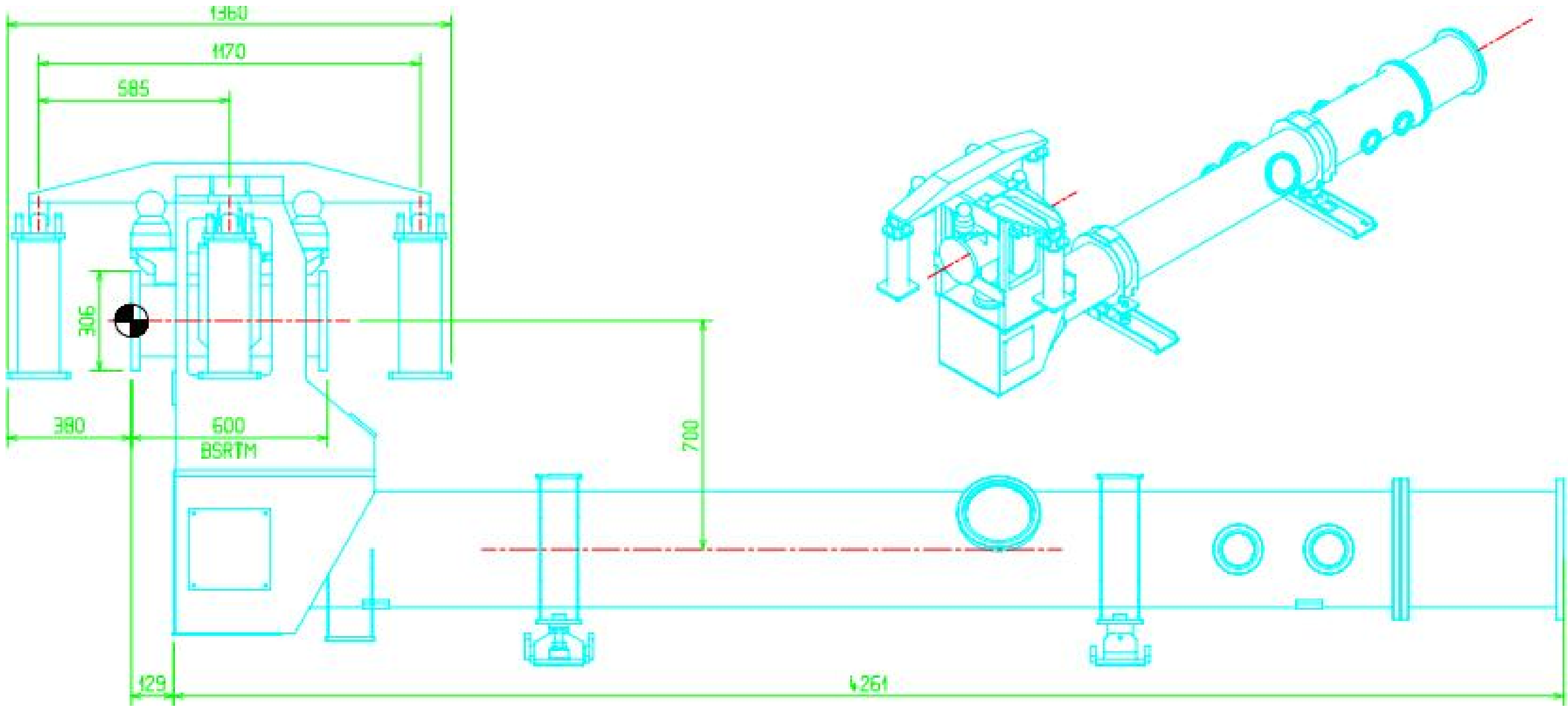
Present Optics

- 2 focusing mirrors
  - Tilted vertically at small angles to normal incidence
- No focusing adjustment
  - Moving a mirror also requires changing its tilt.
  - No room inside the tube to add a delay path (“trombone”) for focusing.
- 4 fold mirrors
- Magnification of 0.28
  - Typical image of 80 μm RMS at 7 TeV

SLM Optics below the Beamline



Optics Housed in a Tube

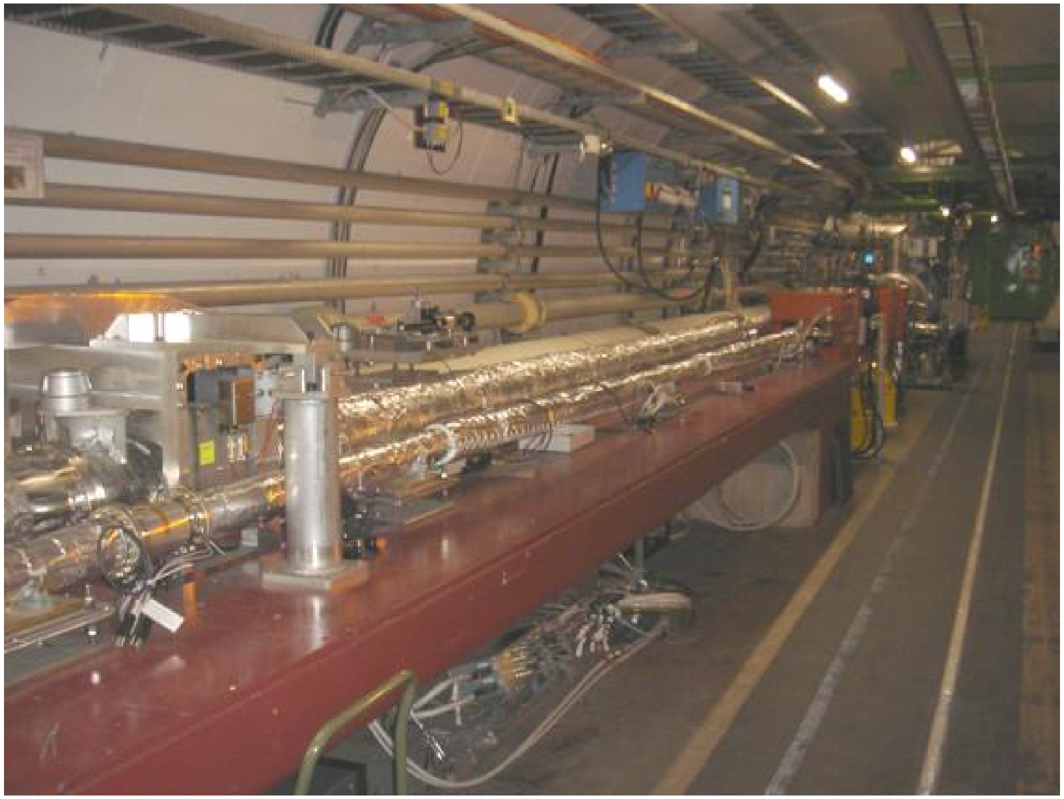


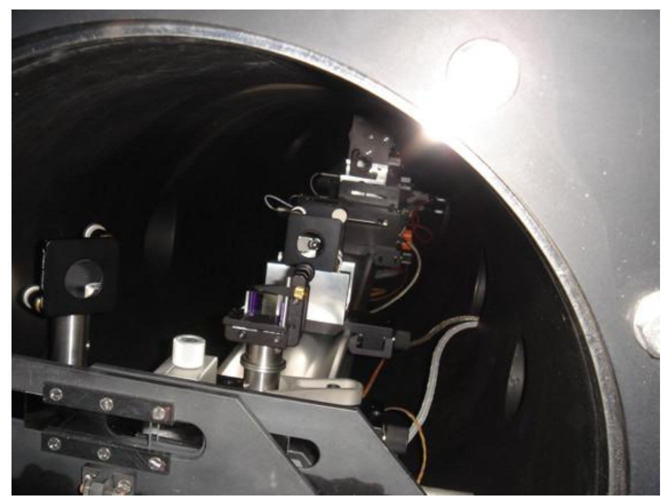
Optics housed in a 4-m-long, LEP-surplus tube, placed under the beamline.

Reasons to Reconsider the Design

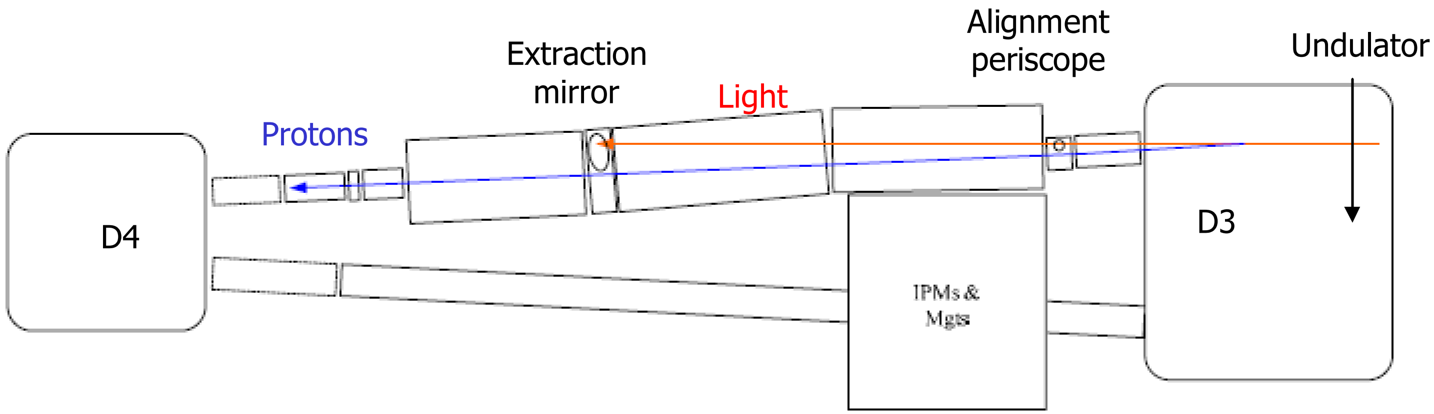
- Mechanics:
  - Replace the tube with an optical table.
    - More space for optics. Better access for adjustment.
- Optics:
  - Add focus adjustment, since source moves during the ramp.
    - Source is in undulator at 450 GeV, but in dipole at 7 TeV.
  - Compute light level from protons and from lead ions.
  - Can the undulator stay on at high energy?
  - Include a calibration source (wouldn’t fit without the table).
  - Evaluate blurring from diffraction and depth of field.
  - Improve the optics for better imaging.
  - Verify that abort gap is empty.

Poor Access with the Present Layout





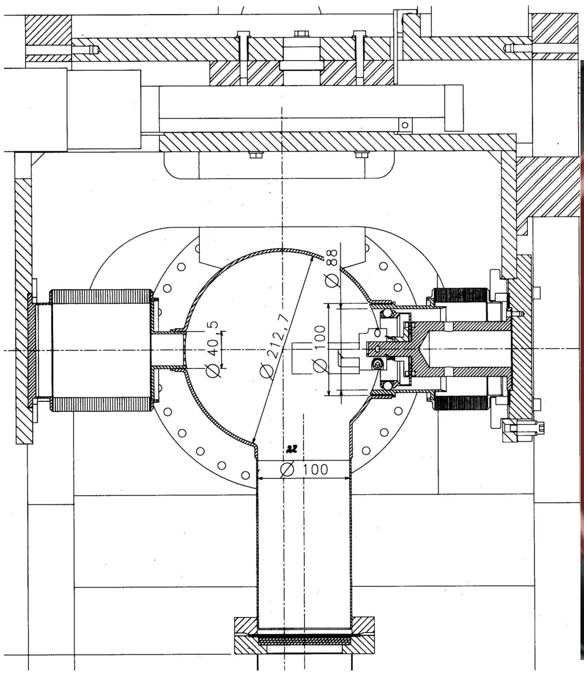
Alignment and Calibration

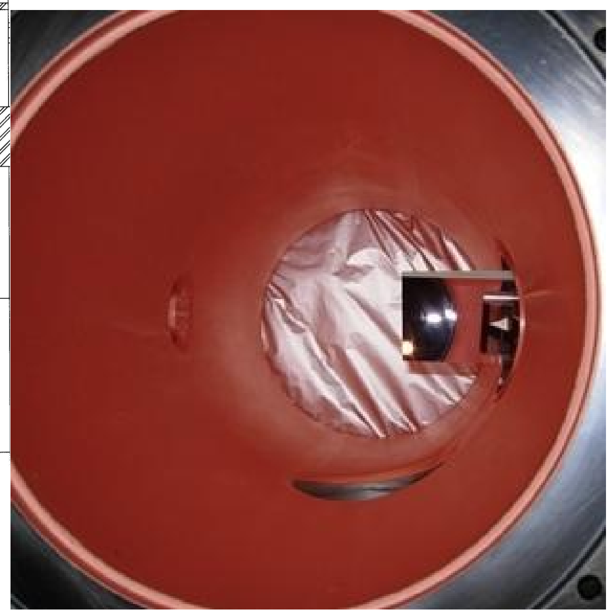


- Alignment periscope brings external laser onto optical path.
  - Useful for aligning the path.
  - Aperture too small to focus and to calibrate image size with a target.
    - Longer depth of field than in real conditions.
    - Difficult to localize the first image plane.
    - Need to use a very powerful diffuse light source.
- Instead, put a calibration laser and target on the optical table.
  - Place target at laser waist matching the divergence angle of the source, and at the source's distance from the optics.

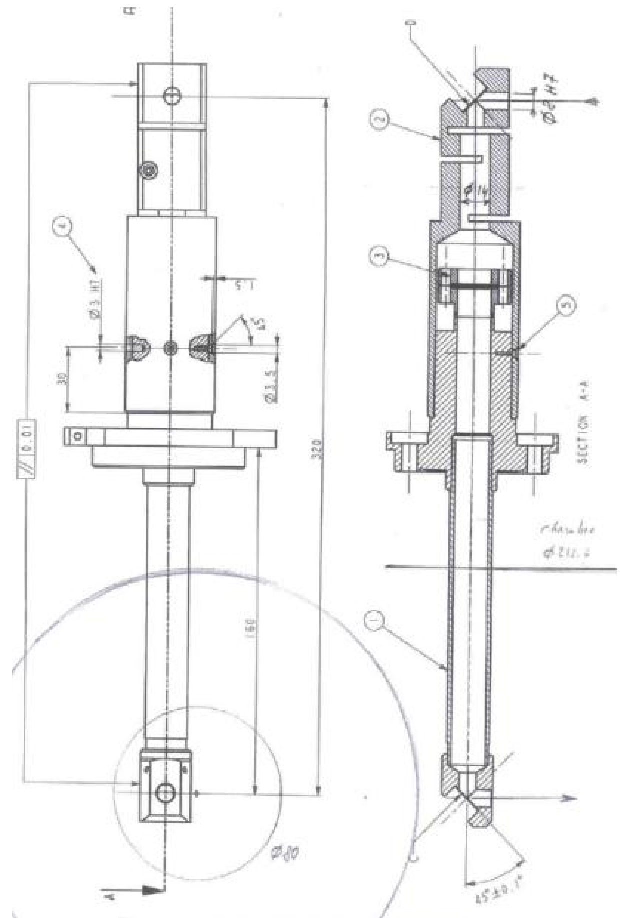
Extraction Mirror, Alignment Periscope

Extraction Mirror





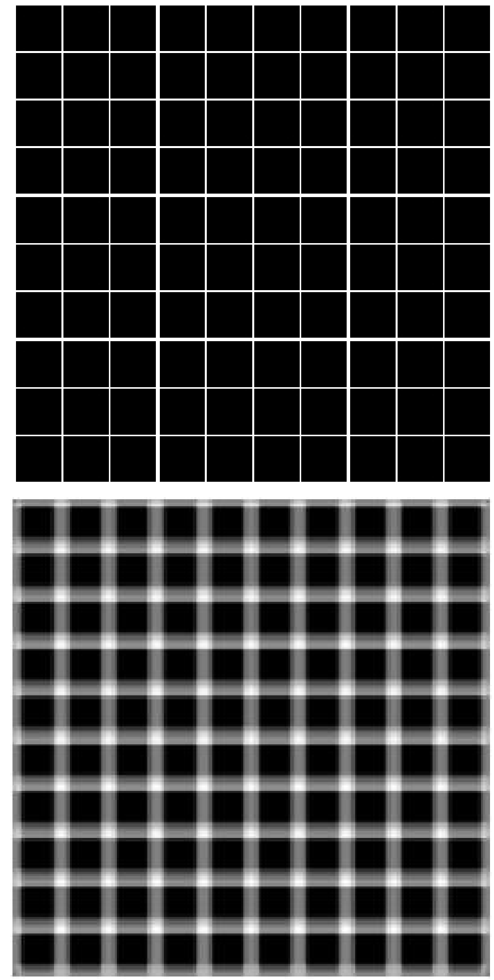
Alignment Periscope



Present Optics: Spherical Mirrors

- Spherical mirrors: aberrations
- Tilted at small angles to normal: more aberrations
- Blurring shown in Zemax simulations
  - Geometric optics only (before diffraction)

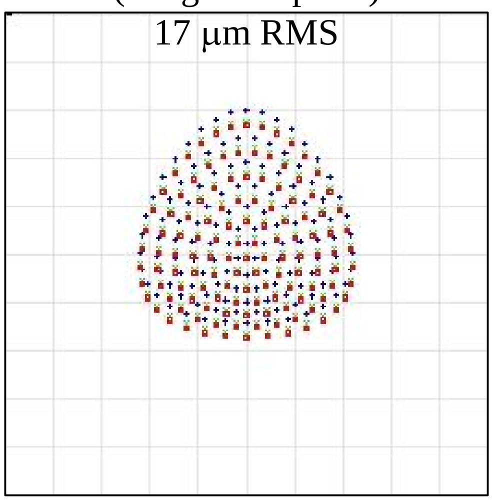
Simulated image of a grid

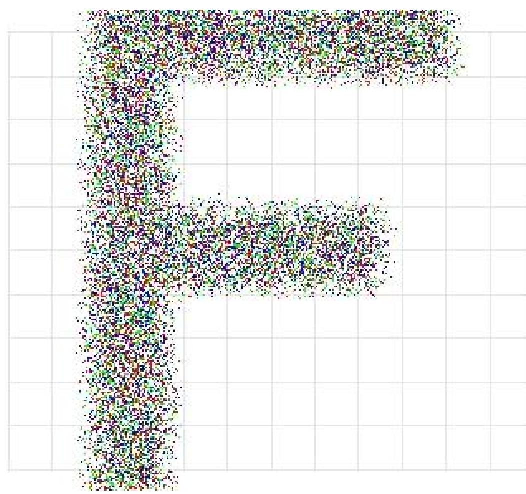


Input

Output

Point-spread function
(image of a point)

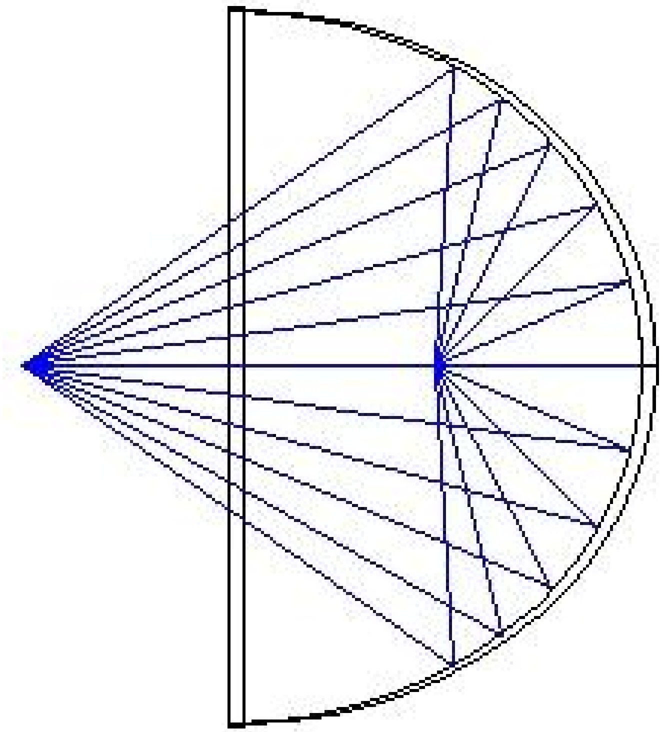




← 100 μm → ← 2 mm → ← 4 mm →

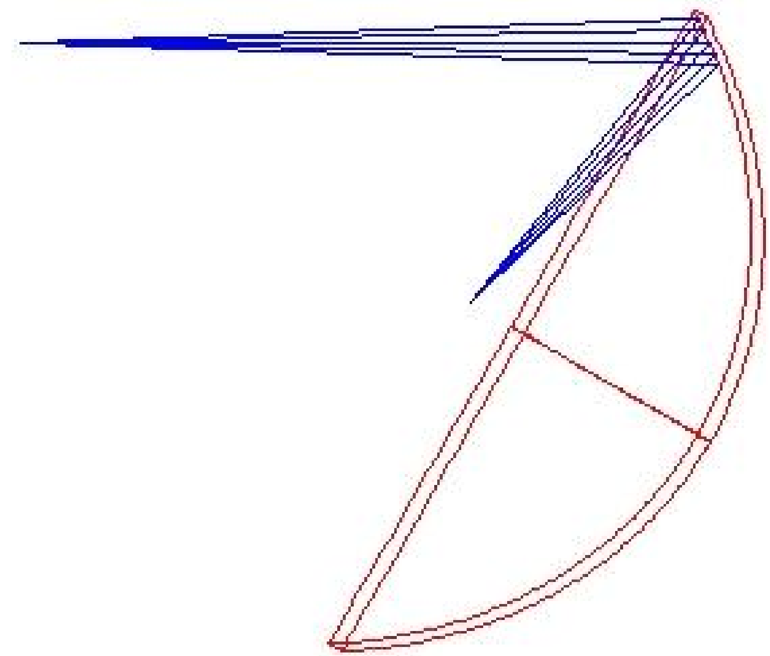
Proposed Optics: Elliptical Mirrors

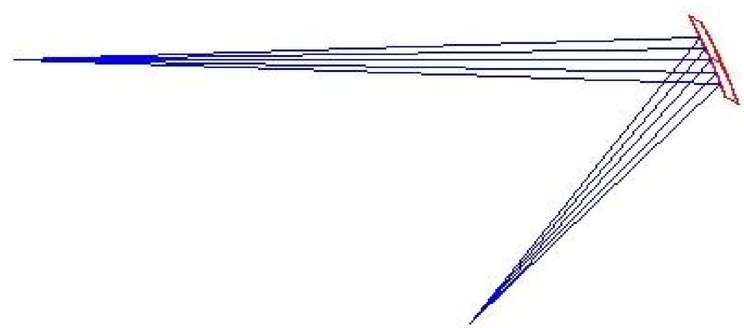
- Continue to use mirrors:
  - Broadband, for infrared from lead ions
  - Radiation resistant
- We want point-to-point imaging
  - Proton/ion beam to camera
- Reflection from an elliptical surface (ellipsoid of revolution) gives geometrically *perfect* point-to-point imaging from one focus to the other.
- But the reflected light interferes with the incoming light…



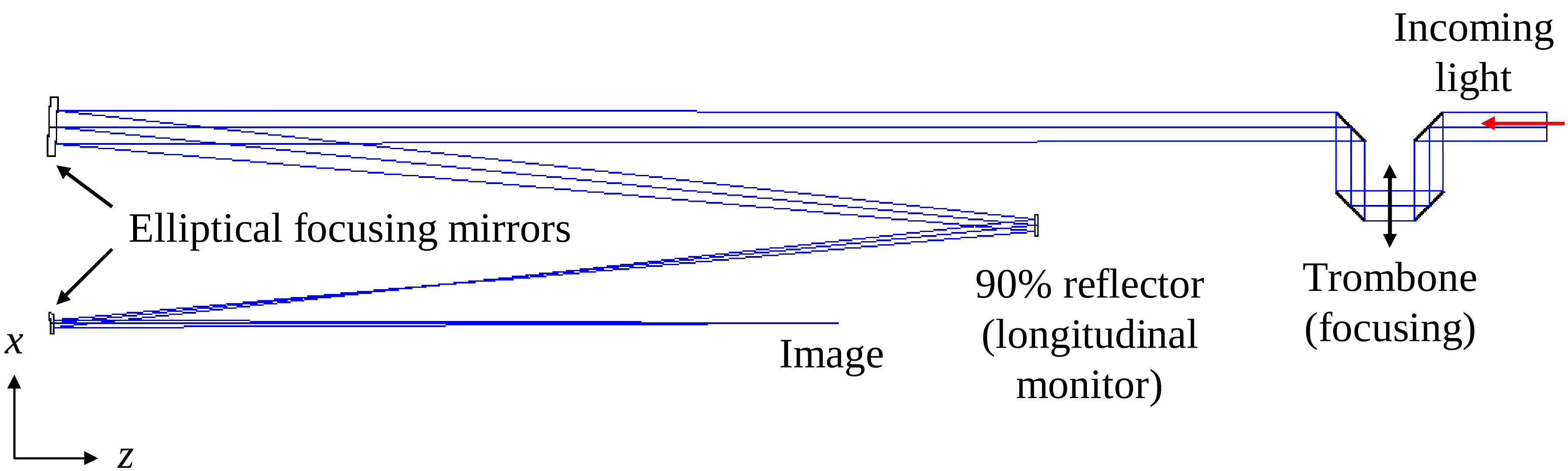
Off-Axis Elliptical Mirrors

- A narrow beam can be both focused *and* steered away from the incoming light by reflecting from an off-axis region of the ellipse.
- The rest of the ellipsoid is not needed and may be removed, leaving a circular mirror with a non-spherical shape.
- Grazing incidence on off-axis conic sections is often used at synchrotron light sources to focus x rays.





Layout with Elliptical Mirrors

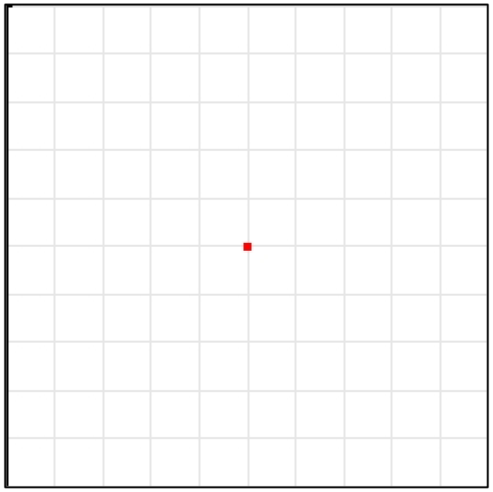


- 2 off-axis elliptical focusing mirrors
- 4-mirror trombone for adjusting focus
  - Requires the optical table for the extra room
- 90% reflector instead of a fold mirror
  - Provides some light for the longitudinal monitor (abort gap)

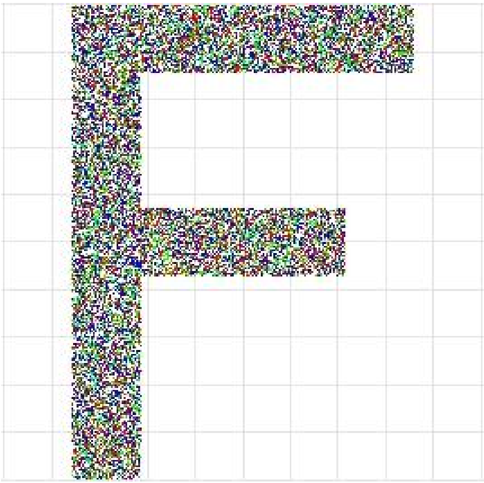
Elliptical Mirrors: Ideal Imaging

- Elliptical mirrors: no aberrations
- Tilted at any angle to normal: still no aberrations
- No blurring in Zemax simulations

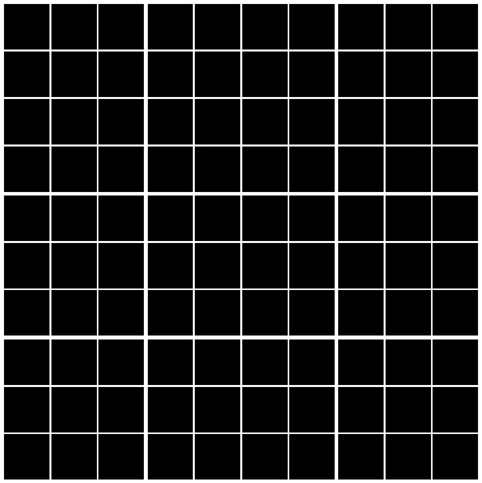
Point-spread function
0 μm RMS



40 nm



2 mm



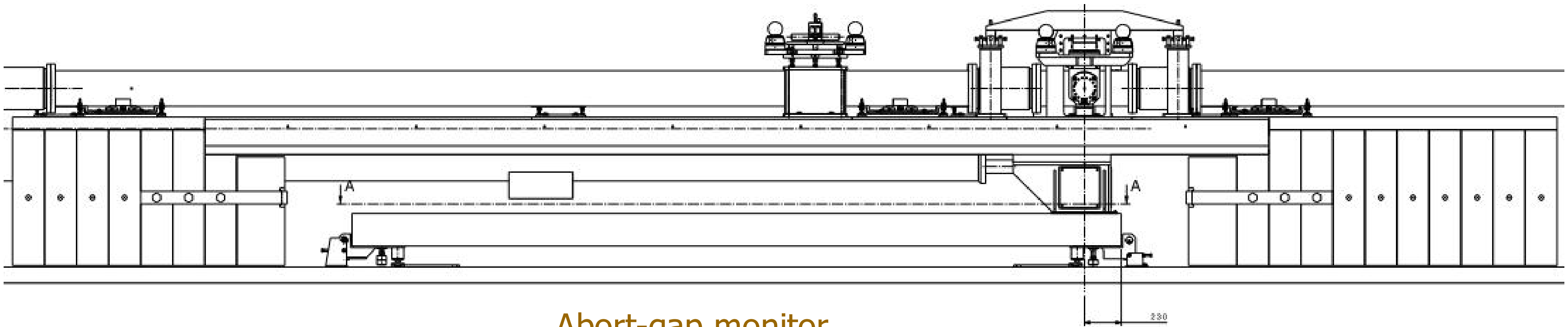
2 mm

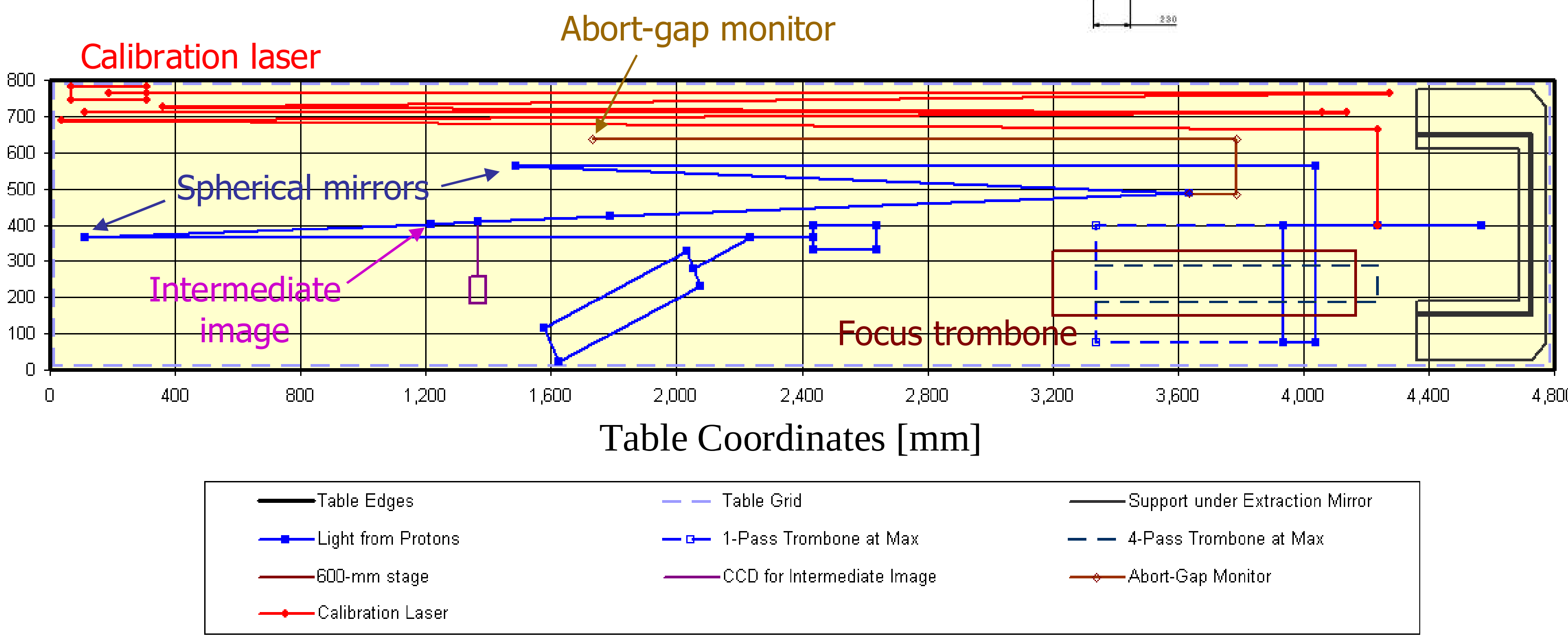
Output

Too Good to be True?

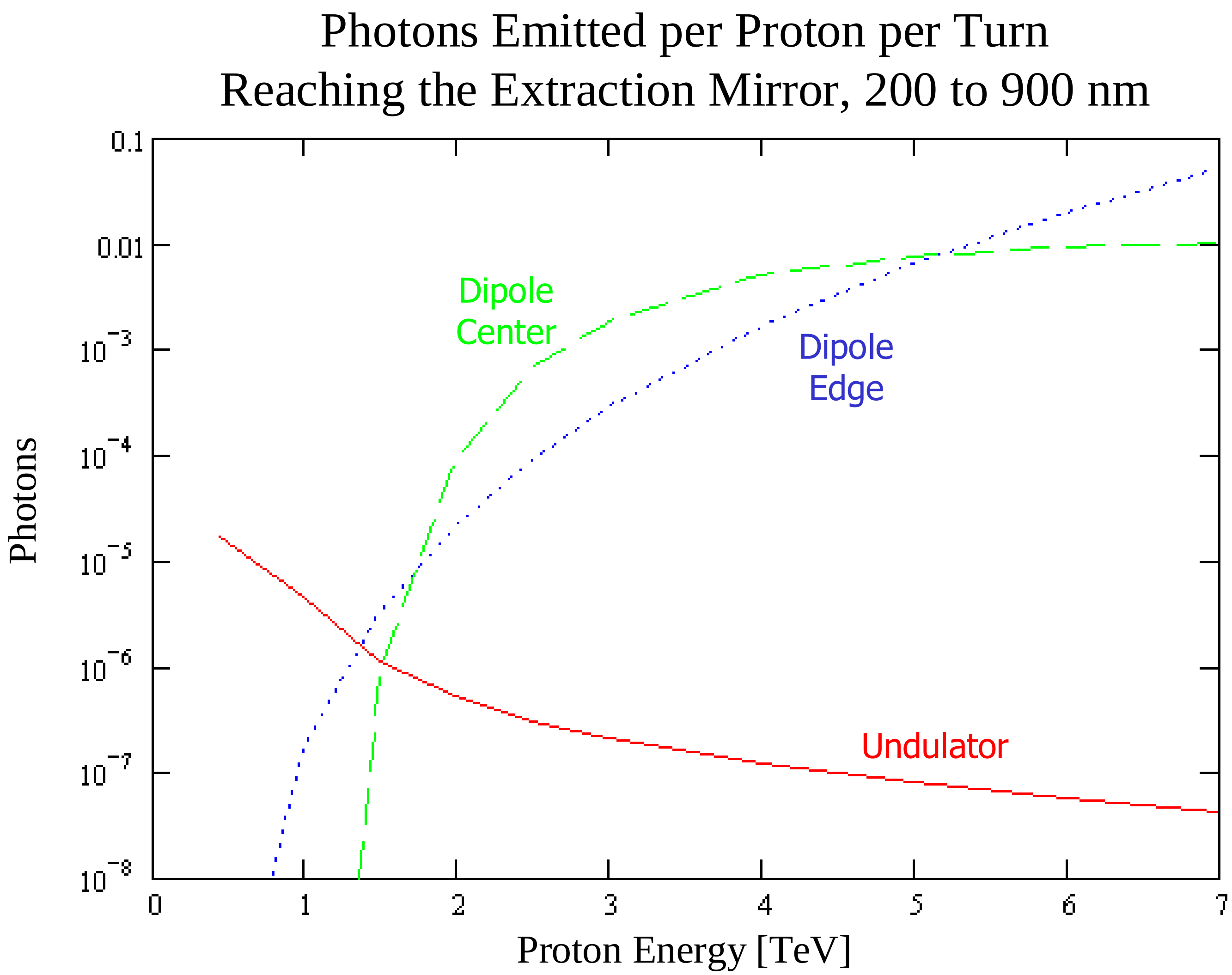
- Elliptical mirrors still form an excellent geometric image (<1 μm RMS) even after including:
  - Source point that is 1 mm (transversely) off the focus
  - Vacuum window, which adds a tiny chromaticity
- Geometric blurring isn't the dominant problem. Next I found bigger problems with:
  - Diffraction
  - Depth of field
- Price:
  - Money available for the optical tables and the focusing trombone, but not for the (expensive) elliptical mirrors.
  - LHC repairs have taken a big bite out of the budget.

Layout for New Optical Table

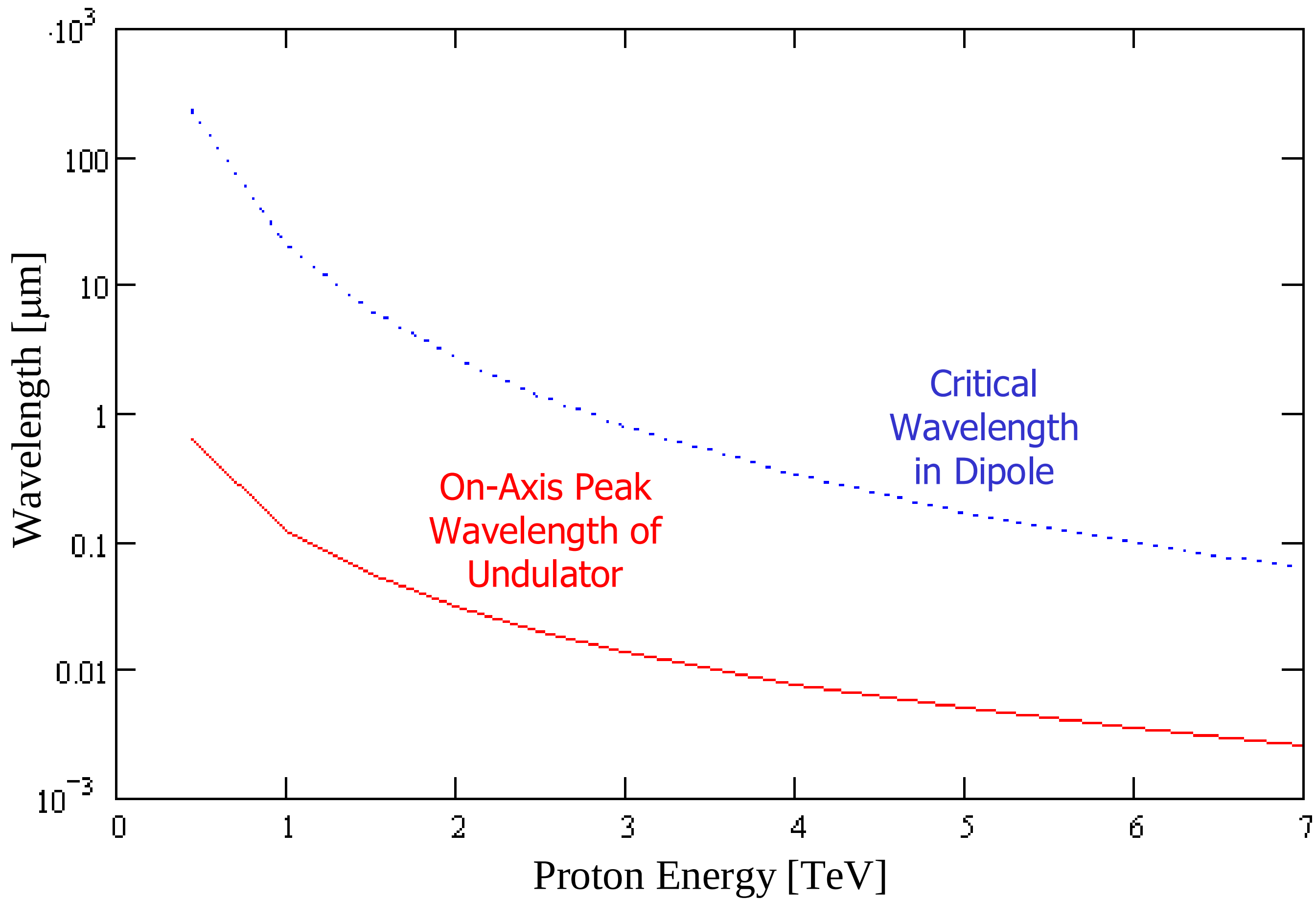




Photons Emitted near the Visible



Peak Wavelength vs. Proton Energy

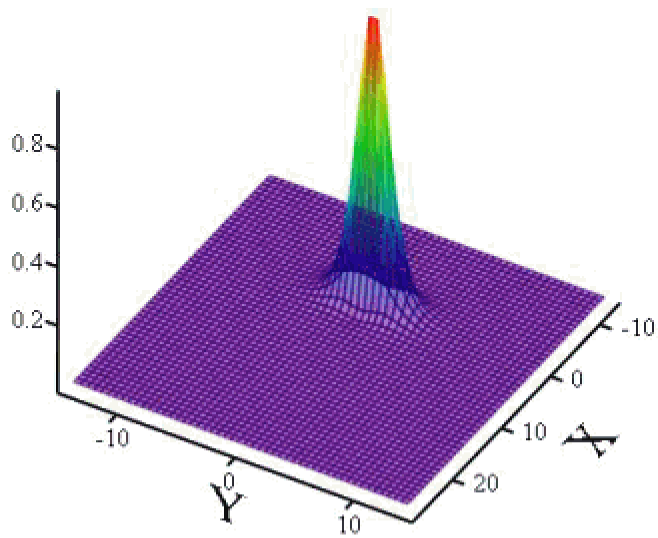


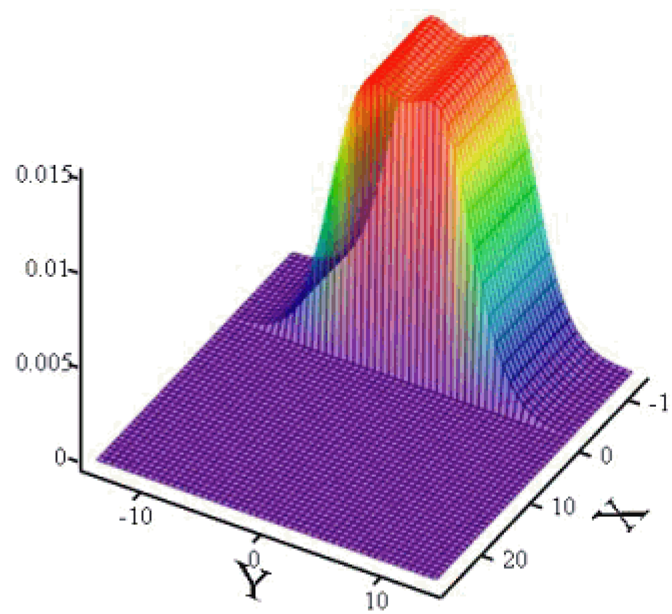
Light on the Extraction Mirror at 7 TeV

Dipole Edge Radiation

Dipole Central Radiation

Sum of horizontal and vertical polarizations between 200 and 900 nm





Radiation Angles

Horizontal	36.9 μrad RMS	497 μrad uniform
Vertical	59.6 μrad RMS	239 μrad RMS

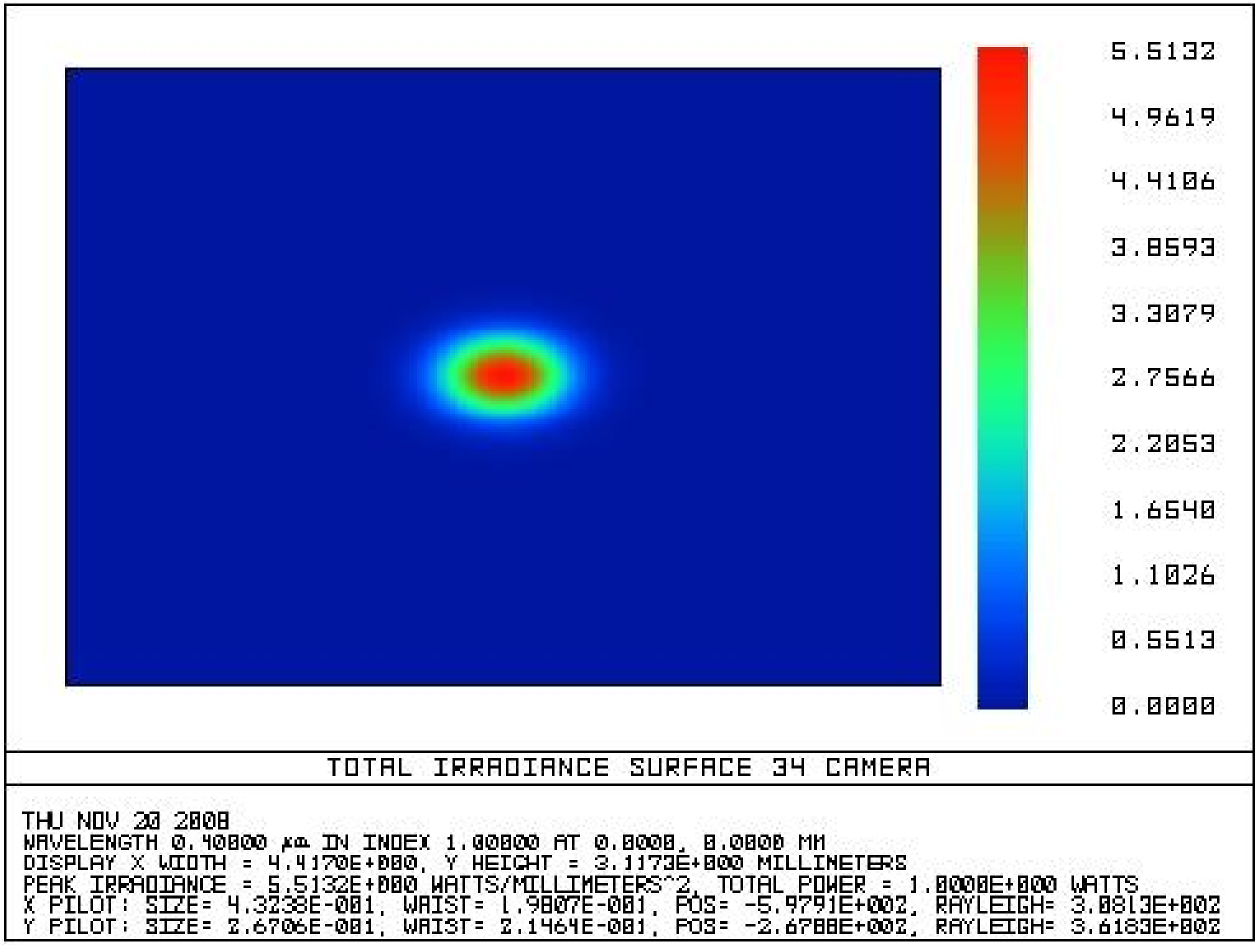
Dipole Edge versus Central Radiation

- CERN planned to measure light from the edge field of the dipole, not from the uniform field inside.
  - More power in the visible at 7 TeV
  - Short depth of field
- But, very narrow cone of edge radiation leads to diffraction.
- For the simplest and narrowest mode, TEM_{00}, the RMS waist size σ_r and divergence angle σ_θ of the source follow:

$$\sigma_r \sigma_\theta = \frac{\lambda}{4\pi}$$

  - An RMS resolution of 100 μm using λ = 400 nm needs an RMS angular spread of 320 μrad.
  - Edge radiation is much narrower than this.
  - Diffraction severely blurs resolution.

Diffraction of Edge Radiation



Using:

λ = 400 nm

x angle of
37 µrad RMS

y angle of
60 µrad RMS

RMS resolution:

x: 220 µm

y: 130 µm

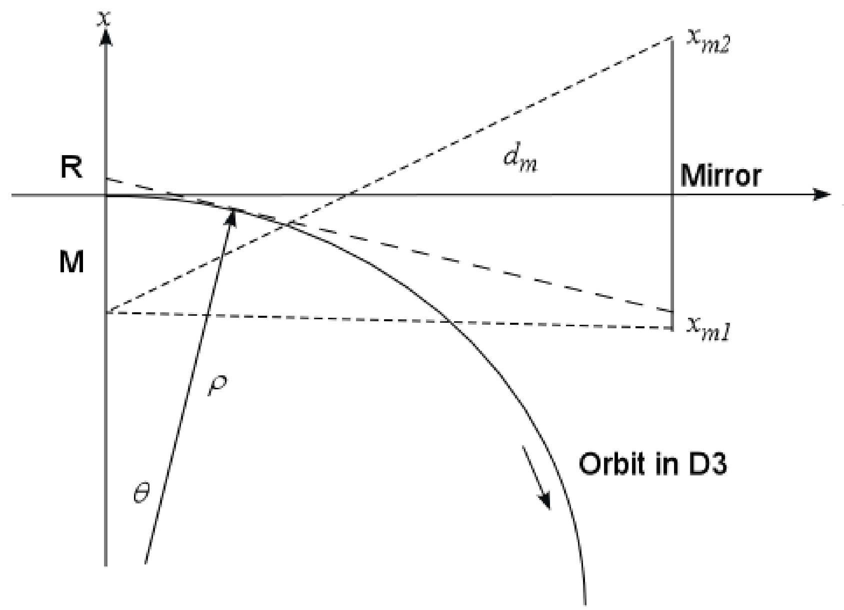
Recall that the beam size on the camera is ≈70 µm.

Edge vs. Central Radiation at 7 TeV

- The visible radiation is 3 to 4 times more intense from the edge compared to the center.
- But the edge radiation has opening angles at 400 nm that are too small for good resolution.
  - What is the diffraction-limited resolution on the image plane from edge radiation?
- A shorter wavelength helps, but the camera response peaks in the visible and drops to zero at 200 nm.
- So, we have to consider using radiation from the uniform-field region of the dipole. But:
  - Extended source along a curved path can blur the image.
  - After restricting the path used, what is the resolution?

Dipole Radiation in *xz* Space

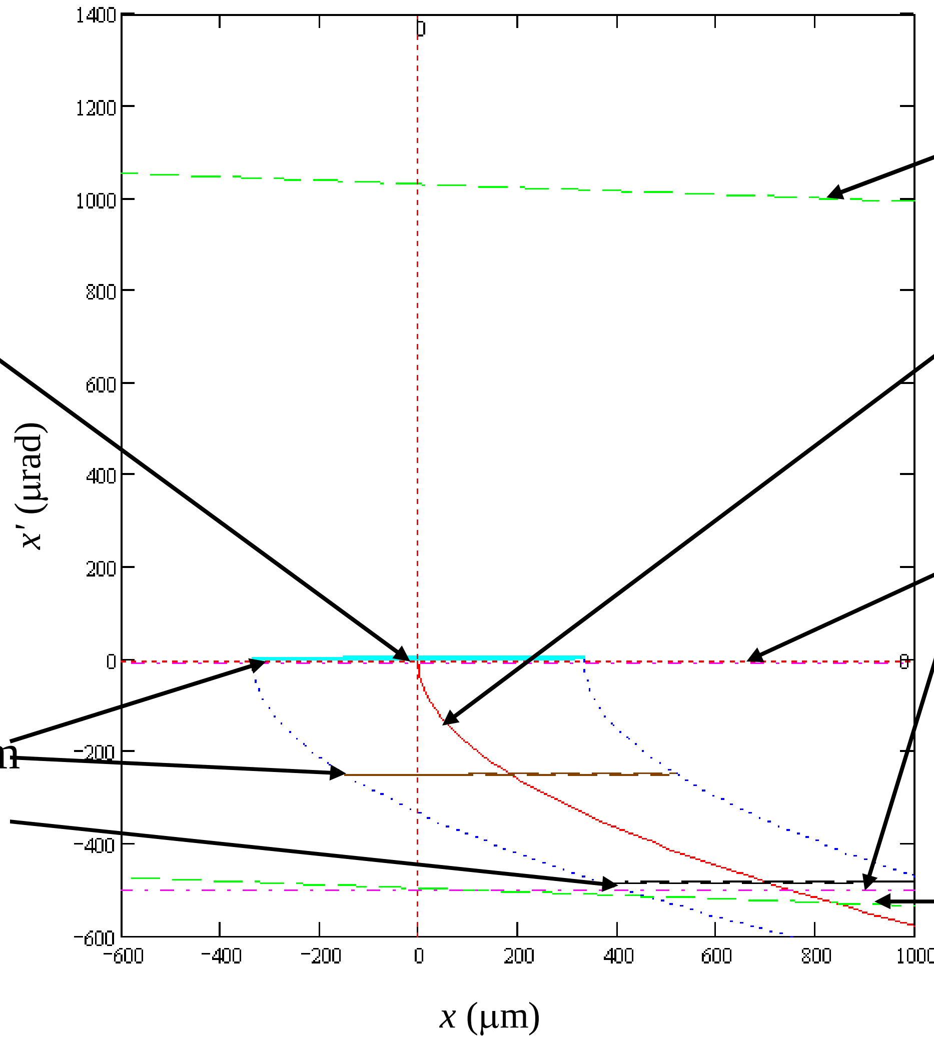
- Consider the beam's orbit in the horizontal plane, first in *xz*, and then in *xx′* phase space.
- Origin at entrance plane of D3.
- Point M shows, for some given point *x*, the range of angles *x′* that can reflect from the extraction mirror.
- Point R shows that a ray emitted inside D3 looks like it was emitted at the entrance with angle $x' = \theta$ and $x = \rho\,(1/\cos\theta - 1) \approx ½\rho\theta^2$



Acceptance in *xx′* Phase Space

Optics focused at dipole entrance

1σ phase-space ellipses of light emitted by the beam at 0, 150, and 290 cm from the dipole entrance.



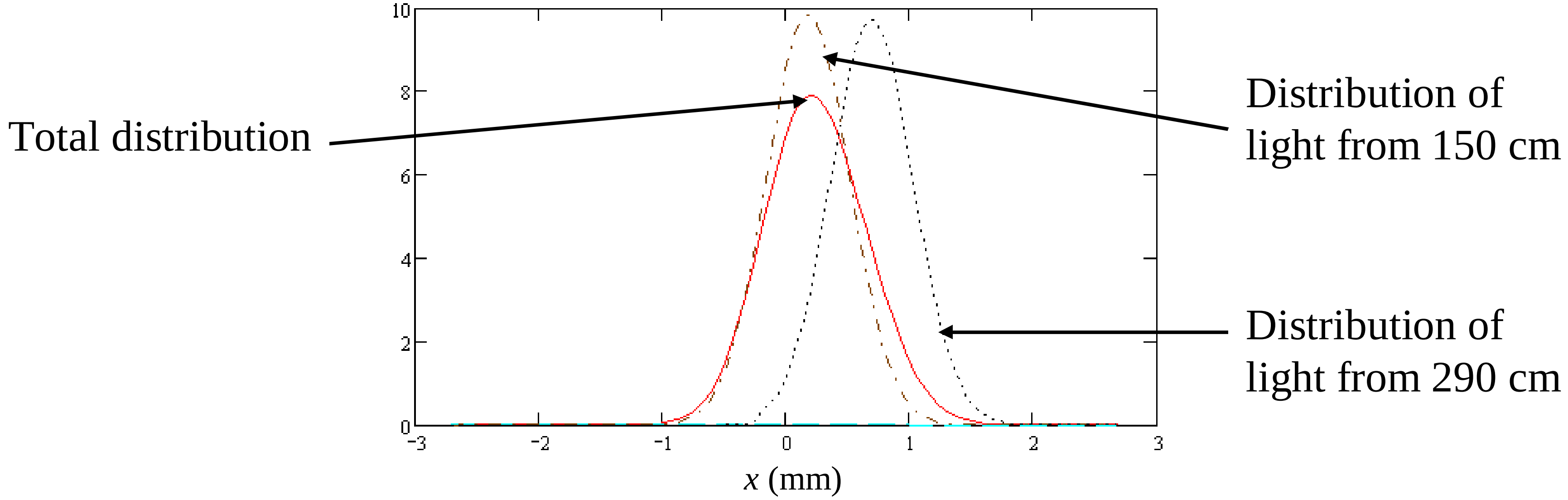
Mirror edge

Orbit: $x = \frac{1}{2}\, \rho\, x'^2$ and $\pm 1\sigma$ to each side

Edges of focal-plane slit accepting light from 5 to 300 cm into D3

Mirror edge: limits light to first 3 m

Combined Horizontal Distribution

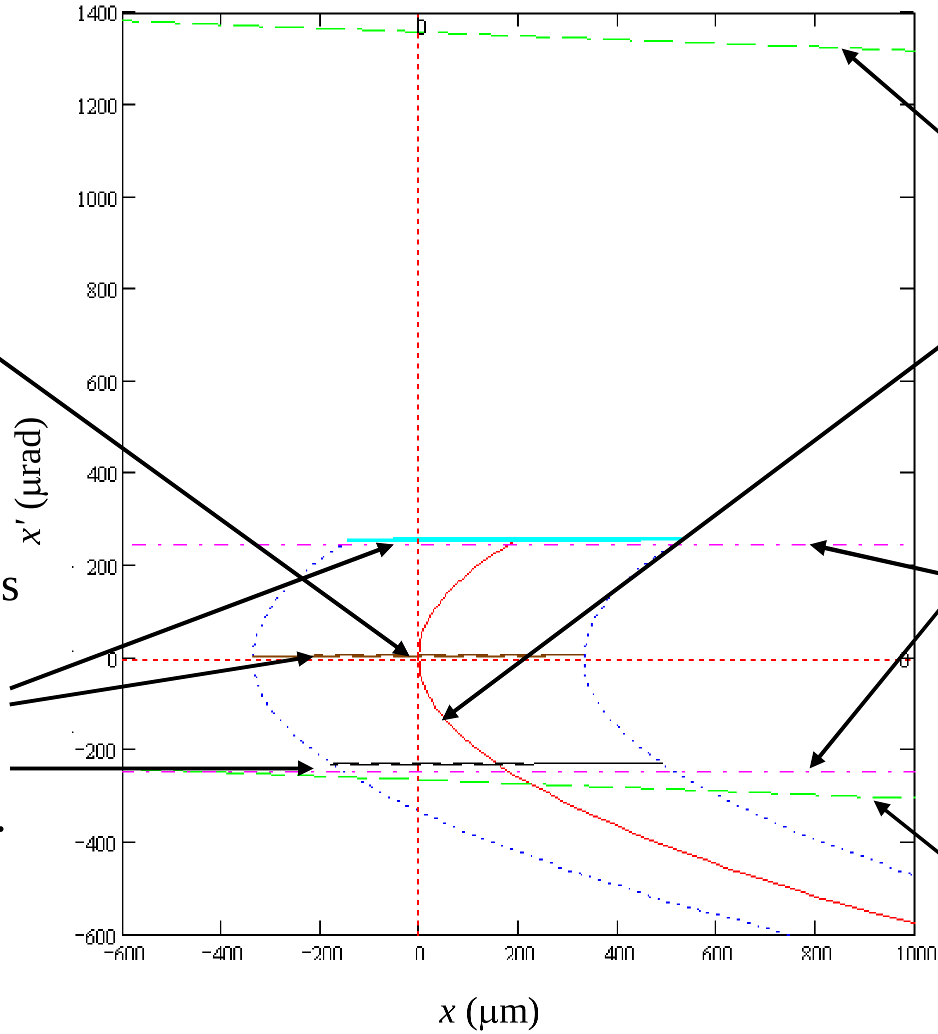


- Slits set to accept 5 to 300 cm of path.
- Optics are focused at 0 cm (dipole entrance).
- Project the light emitted along this path onto the *x* axis of this focal plane.
- Also show distributions on focal plane of light from typical points on path.
- Effect of extended source (depth of field):
  - The beam in this calculation has a true width of 334 μm (at middle of path).
  - The total projection (red) is 408 μm wide and shifted right by 255 μm.

Increased Acceptance: Focus in Dipole

Focus and *xz* origin moved to midpoint of slits, 152.5 cm inside dipole

Phase-space ellipses of light emitted by the beam at 0, 150, and 290 cm from the dipole entrance.



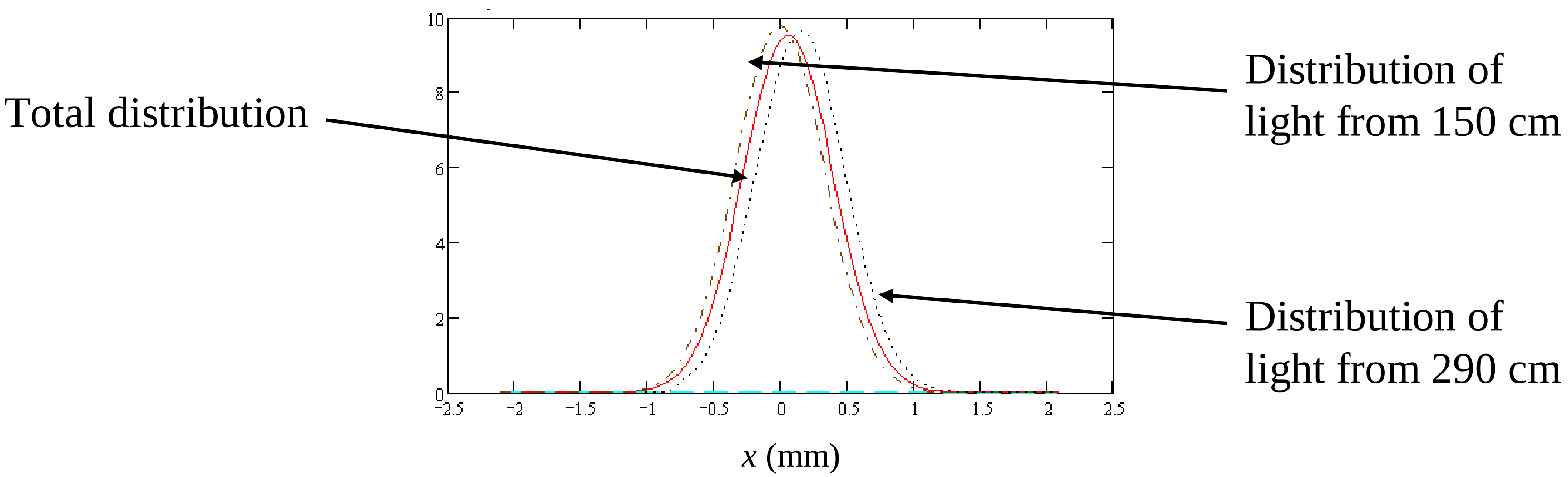
Mirror edge

Orbit: $x = \frac{1}{2}\,\rho\, x'^2$ and $\pm 1\sigma$ to each side

Edges of focal-plane slit accepting light from 5 to 300 cm into D3

Mirror edge

Focus at 152 cm: Horizontal



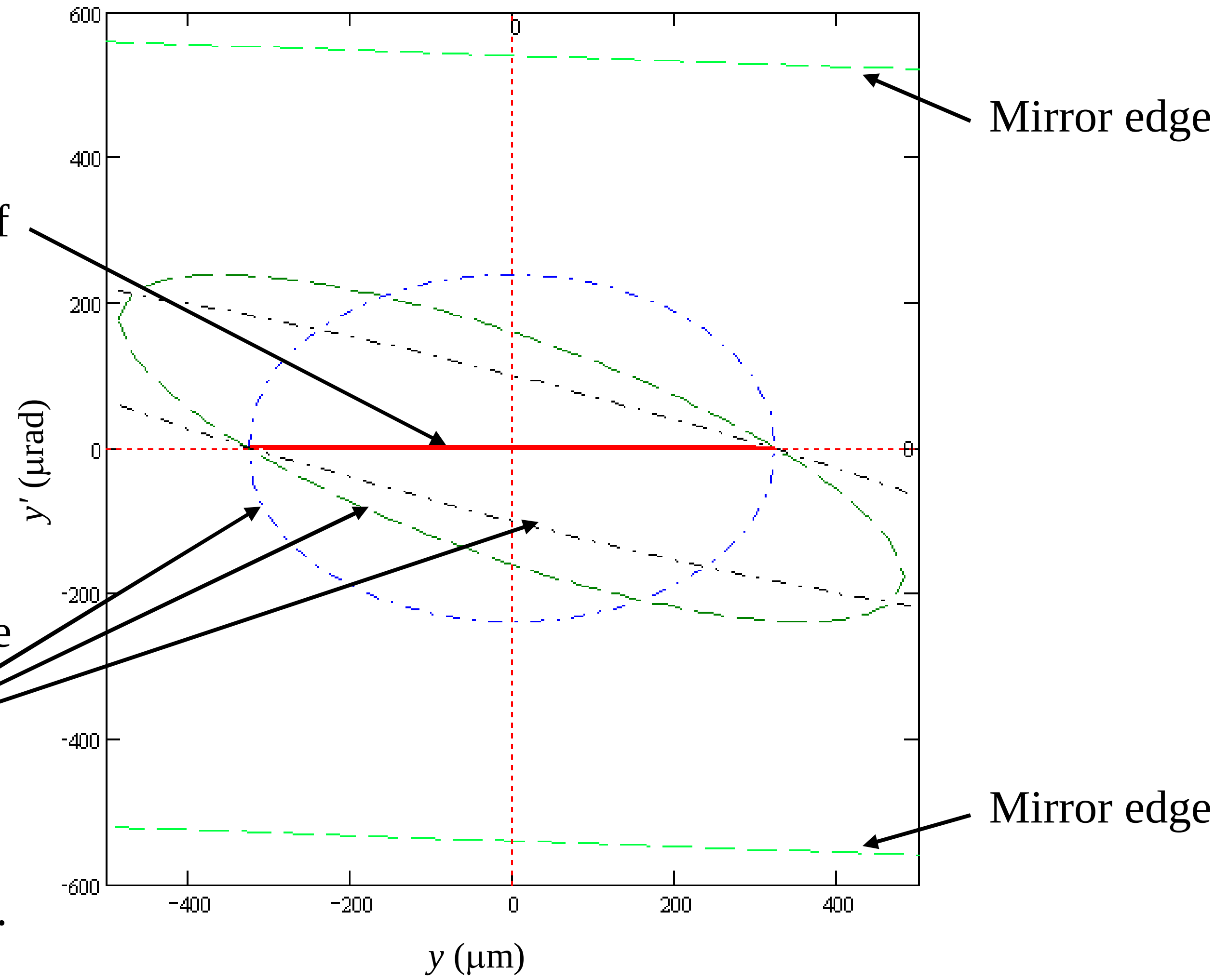
- Only small shifts in *x* of emission from each point on path.
- Very little depth-of-field trouble:
  - True width = 336 μm.
  - Width of projection (red) = 341 μm.

Acceptance in Vertical Phase Space

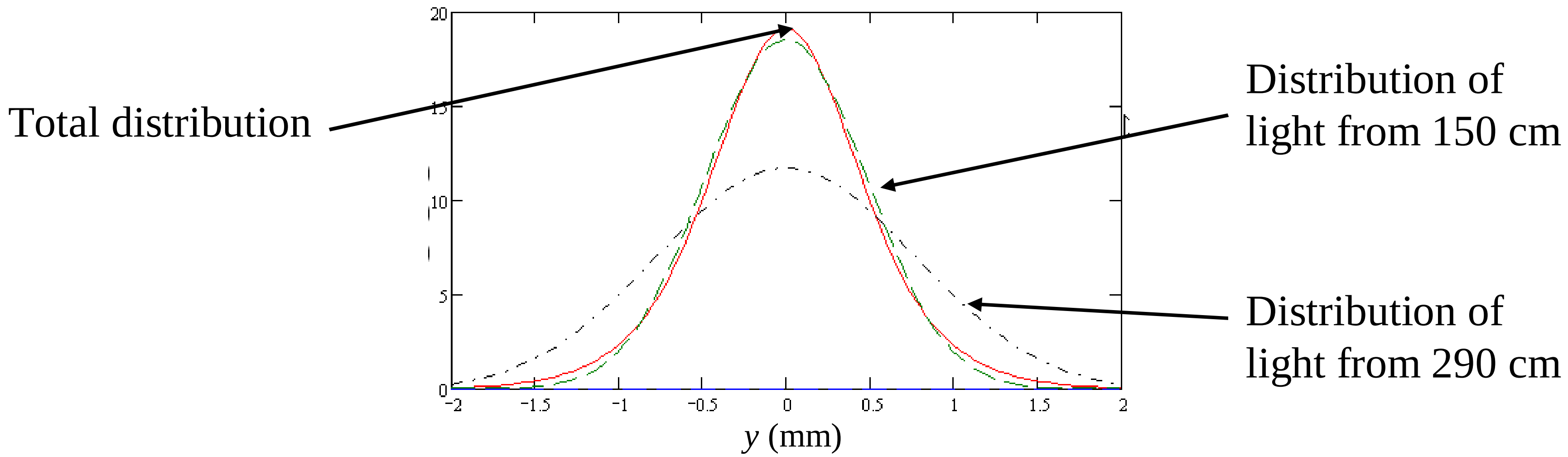
Optics focused at entrance to dipole

Phase-space ellipse of the protons at dipole entrance

Phase-space ellipses of light emitted by the beam at 0, 150, and 290 cm from the dipole entrance. Enlarged by opening angle of the radiation.



Combined Vertical Distribution



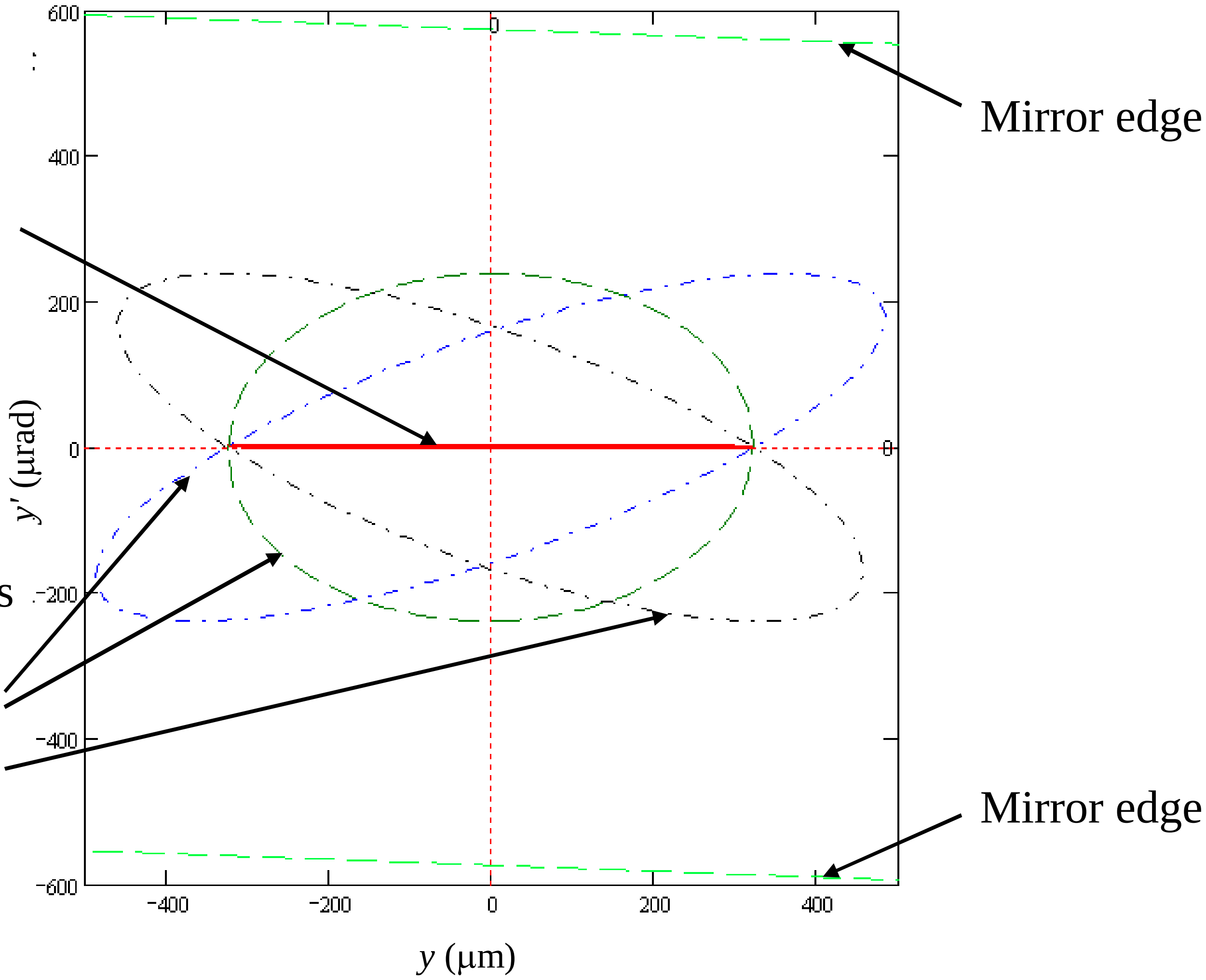
- As before, slits accept 5 to 300 cm of path, and optics focused at 0 cm.
- Project the light emitted along this path onto the *y* axis of this focal plane.
  - Expect big broadening when combining ellipses with different skews.
  - Ray angles widen curve as emission point gets further from focus.
  - No vertical bending, and so no shift.
- True width = 324 μm; width of projection (red) = 510 μm.

Focus at 152 cm: Vertical Phase Space

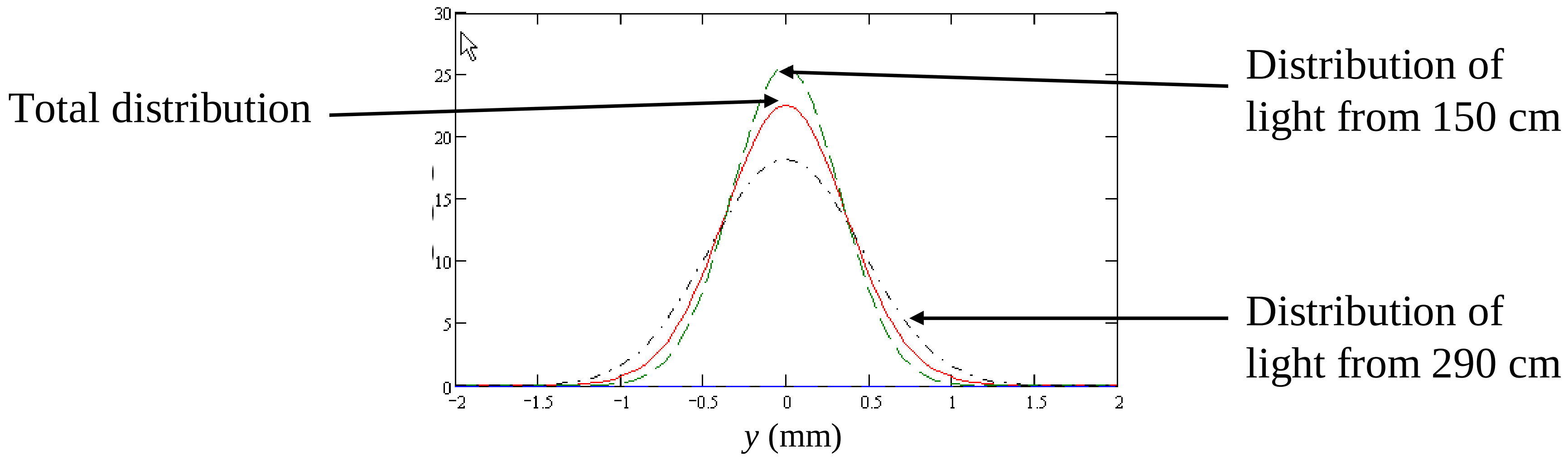
Optics focused at entrance to dipole

Phase-space ellipse of the protons at dipole entrance

Phase-space ellipses of light emitted by the beam at 0, 150, and 290 cm from the dipole entrance.



Focus at 152 cm: Vertical Distribution

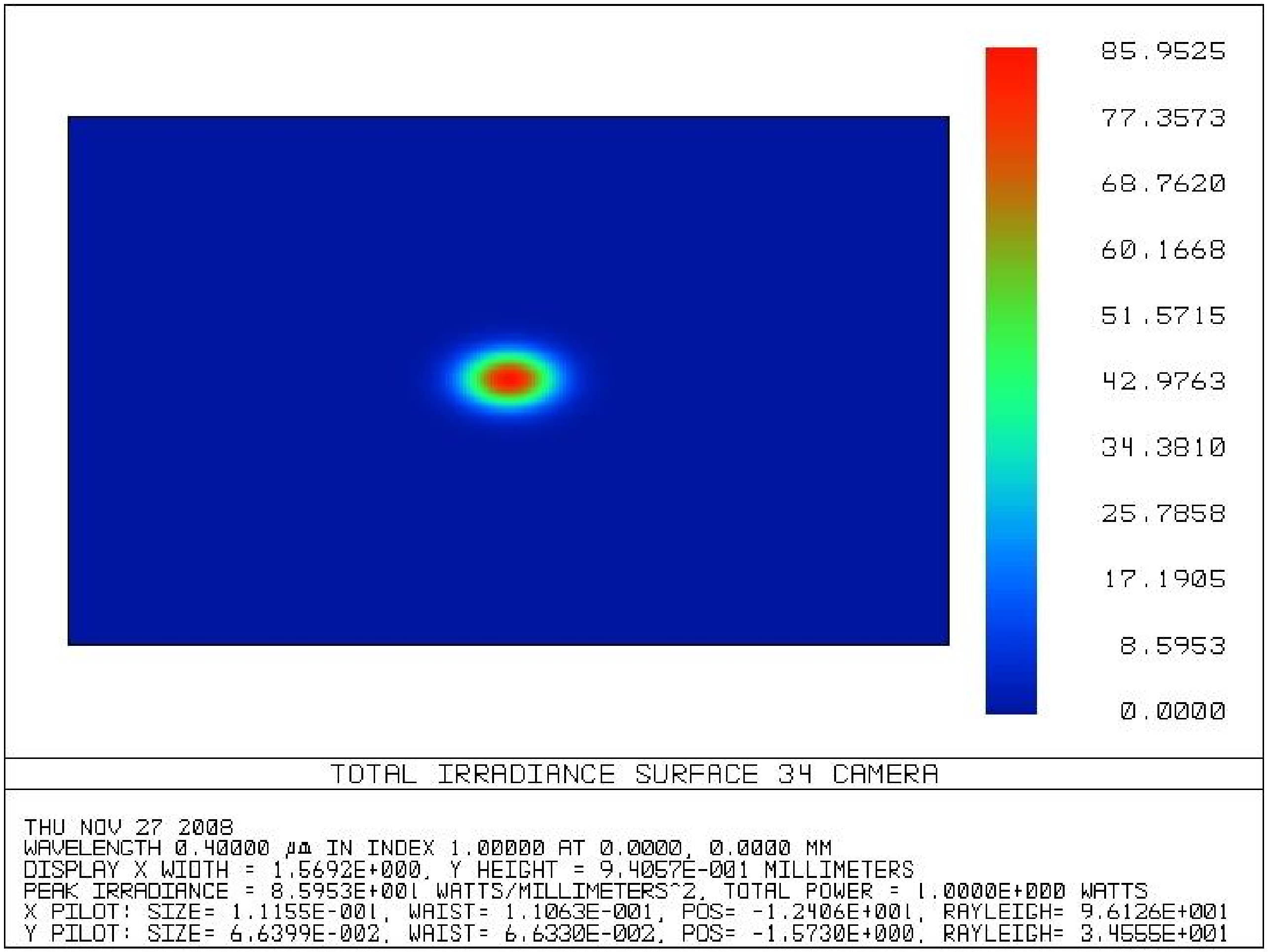


- Narrower ellipses: less broadening of distribution.
- True width = 323 μm; width of projection (red) = 378 μm.

Using a Long Path in the Dipole

- So we can combine light from the first 3 m of D3, all that the extraction mirror accepts, and get tolerable broadening of the measurement.
- But what happens when we add diffraction?
- Calculate the total broadening, from both the extended source and diffraction.

Diffraction of Central Radiation



295-cm path with focus at center.

Using:

- λ = 400 nm
- *x* angle of 284 µrad RMS
- *y* angle of 239 µrad RMS

RMS resolution:

- *x*: 56 µm
- *y*: 33 µm

Predicted Measurements of Beam Size

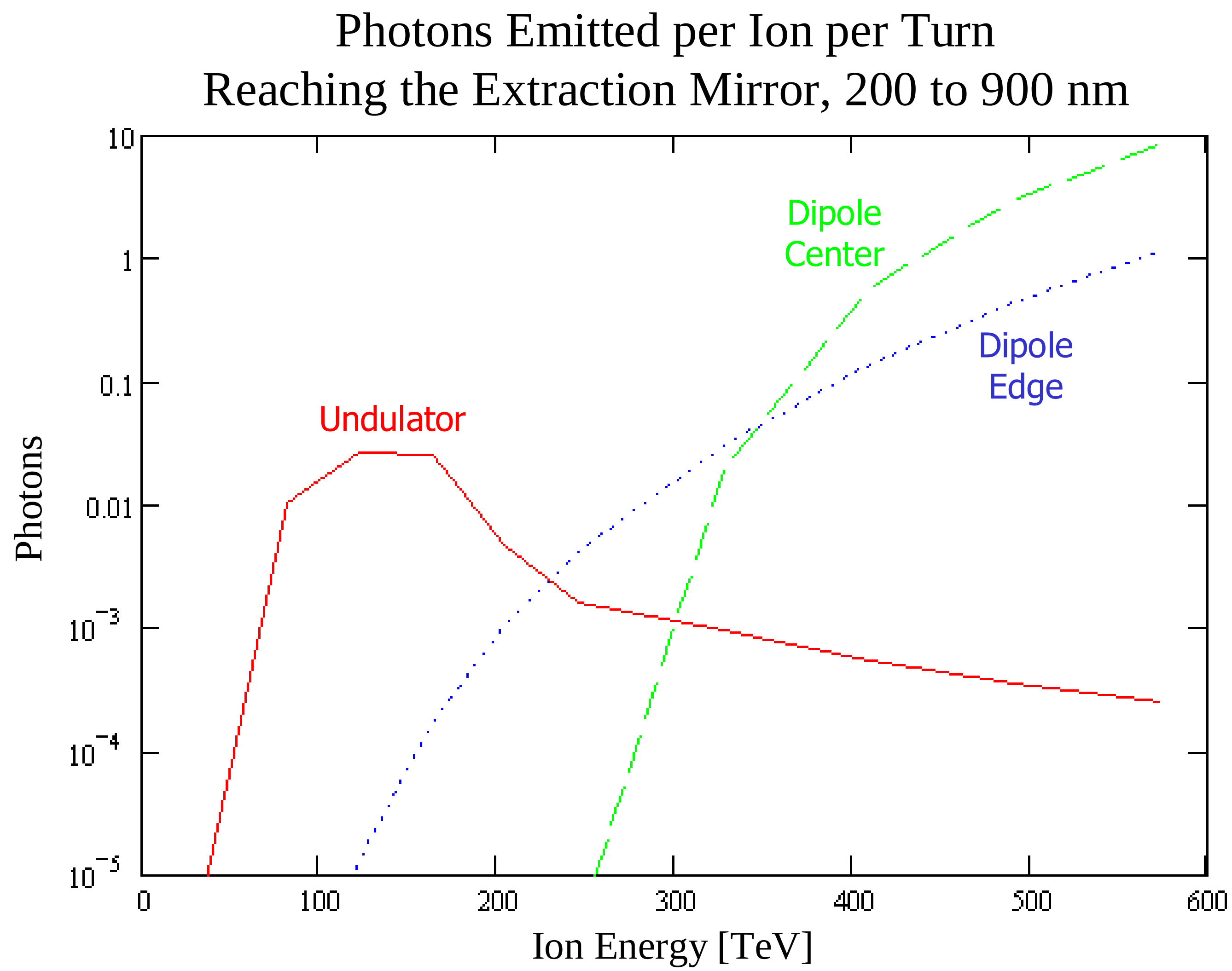
Path in D3 Transmitted by			Beam Size at Source		Beam Size Blurred by Path in D3			Emission Angle at 400-nm		Ideal Size at Camera		Diffraction Resolution		Expected Measurement at Camera			
Start	Focus	End	Horiz	Vert	Horizontal		Vertical	Horiz	Vert	Horiz	Vert	Horiz	Vert	Horizontal		Vertical	
cm	*cm*	*cm*	*mm RMS*	*mm RMS*	*Offset mm*	*Size mm RMS*	*mm RMS*	*mrad RMS/Flat*	*mrad RMS*	*mm RMS*	*mm RMS*	*mm RMSx2*	*mm RMSx2*	*mm RMS*	*Fractional Change*	*mm RMS*	*Fractional Change*
								(RMS)									
Edge	0	Edge	334.1	324.3	0.0	334.1	321.1	36.9	59.6	83.5	81.1	429.3	265.9	214.7	2.57	132.9	1.64
								(Flat)									
5	0	25	334.1	324.3	2.2	337.9	326.4	33.4	238.7	83.5	81.1	1650.9	66.4	825.5	9.88	81.3	1.00
5	0	50	334.1	324.3	7.9	336.6	331.5	75.1	238.7	83.5	81.1	732.3	66.4	366.1	4.38	82.5	1.02
5	0	100	334.1	324.3	29.8	337.4	350.7	158.5	238.7	83.5	81.1	346.6	66.4	173.3	2.07	87.3	1.08
5	0	150	334.1	324.3	65.4	341.8	380.3	241.9	238.7	83.5	81.1	227.0	66.4	113.5	1.36	94.7	1.17
5	0	200	334.1	324.3	114.8	352.5	418.2	325.4	238.7	83.5	81.1	168.8	66.4	87.8	1.05	104.1	1.28
5	0	250	334.1	324.3	177.9	373.4	462.3	408.8	238.7	83.5	81.1	134.3	66.4	93.0	1.11	115.1	1.42
5	0	300	334.1	324.3	254.7	407.7	510.0	492.2	238.7	83.5	81.1	111.6	66.4	101.5	1.22	127.0	1.57
								(Flat)									
5	15	25	334.3	324.2	0.3	337.7	324.5	33.4	238.7	83.6	81.0	1650.9	66.4	825.5	9.88	80.8	1.00
5	27.5	50	334.5	324.1	1.6	336.2	325.4	75.1	238.7	83.6	81.0	732.3	66.4	366.1	4.38	81.0	1.00
5	52.5	100	334.8	324.0	6.9	335.8	329.8	158.5	238.7	83.7	81.0	346.6	66.4	173.3	2.07	82.1	1.01
5	77.5	150	335.2	323.8	15.6	336.1	337.4	241.9	238.7	83.8	81.0	227.0	66.4	113.5	1.35	84.0	1.04
5	102.5	200	335.5	323.7	27.8	336.9	348.1	325.4	238.7	83.9	80.9	168.8	66.4	84.4	1.01	86.7	1.07
5	127.5	250	335.9	323.5	43.5	338.4	361.5	408.8	238.7	84.0	80.9	134.3	66.4	84.3	1.00	90.0	1.11
5	152.5	300	336.3	323.3	62.9	340.9	377.5	492.2	238.7	84.1	80.8	111.6	66.4	84.9	1.01	94.0	1.16

- Measurement using magnet edge (top row) is dominated by diffraction.
  - Details of the diffraction calculation on next slides.
- For light from inside dipole, having focus centered in slit’s range helps.
- Best balance of *x* and *y* sizes, and of total light collected, uses 2 to 3 m.

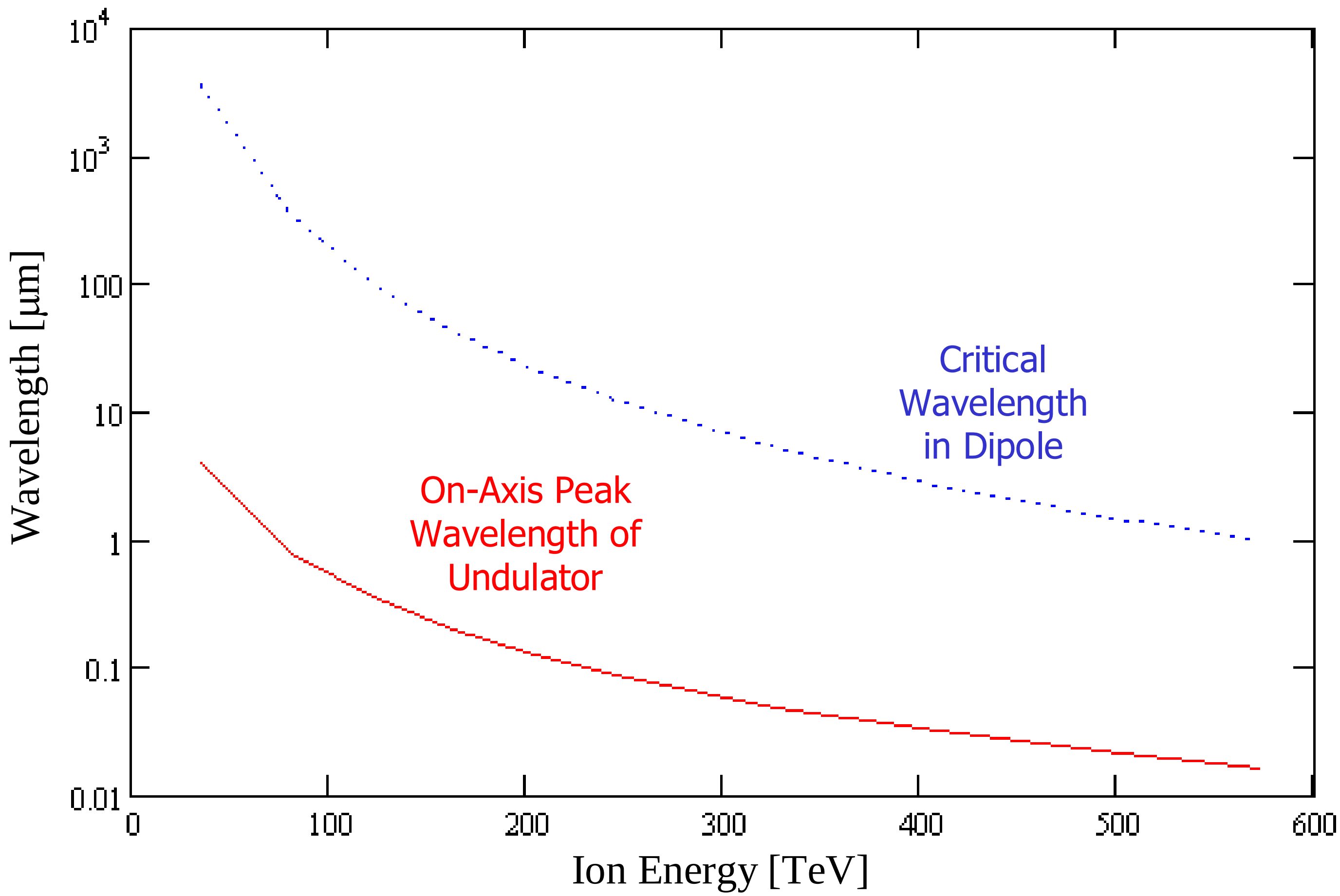
Synchrotron Light from Heavy Ions

- ALICE will study collisions of lead ions.
- Planned for ~3 weeks in 2010, at the end of the run.
- Ion energy determined by maximum dipole field:
  - Inject at 36.9 TeV/ion, or 177 GeV/nucleon
  - Collide at 574 TeV/ion, or 2.76 TeV/nucleon
    - 82 times the kinetic energy of a mosquito at 1 m/s
    - Kinetic energy of a 1-mm-diameter grain of sand at 40 km/h
- Fewer bunches and fewer particles/bunch:
  - Ions: 592 bunches of $8.2\times10^{9} = 4.9\times10^{12}$
  - Protons: 2808 bunches of $1.2\times10^{11} = 3.4\times10^{14}$
  - Similar quench limit

Photons Emitted near the Visible

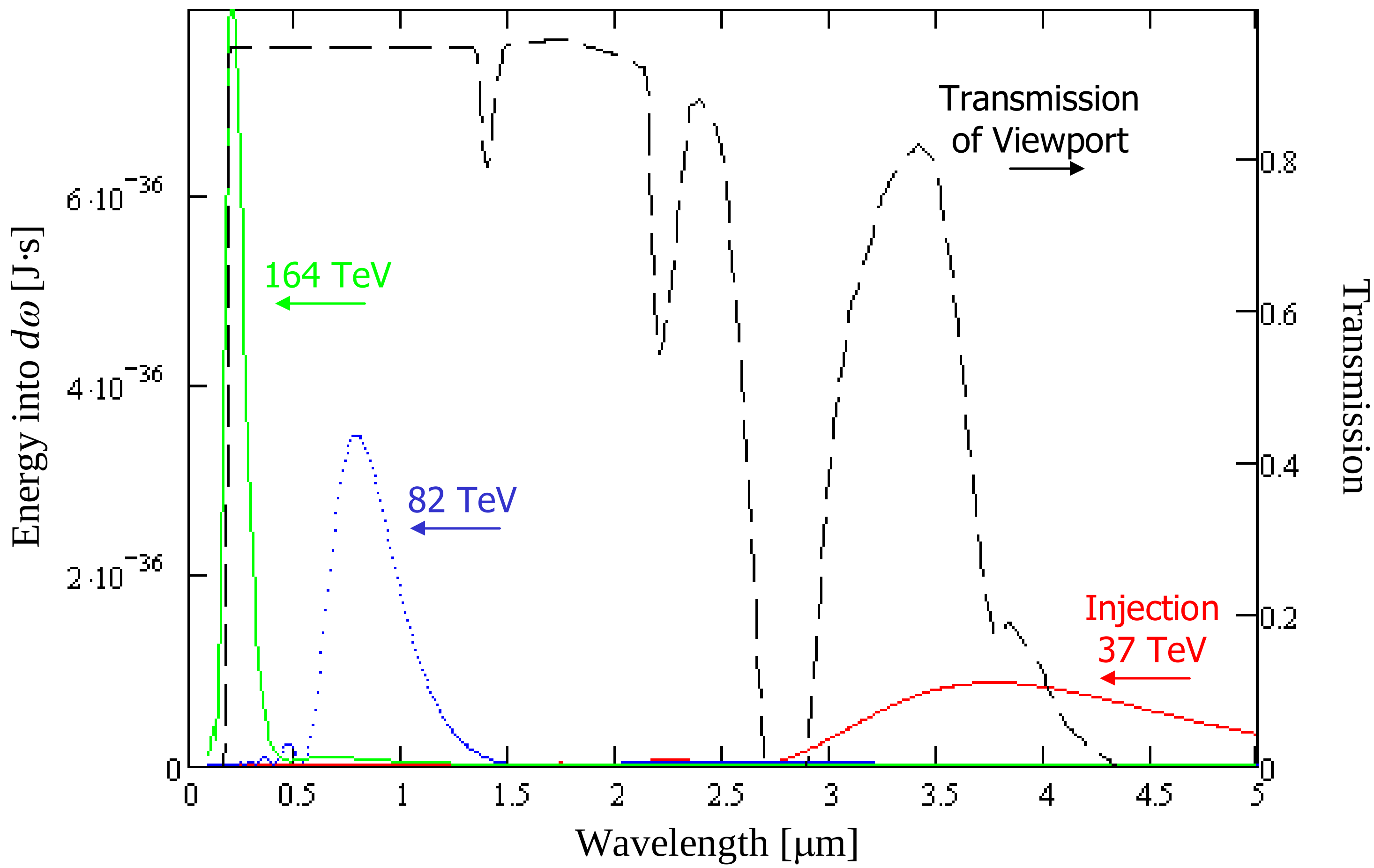


Peak Wavelength vs. Ion Energy



Undulator Spectra of Low-Energy Ions

Undulator spectra for lead ions at three energies, corresponding to protons at 0.45, 1, and 2 TeV



Next Steps

- Table and focusing stage have been ordered.
- Defer the upgrade of the focusing optics.
  - Blurring is dominated by diffraction.
  - Elliptical optics are expensive.
    - A lot of this year's money has gone into LHC repairs.
- Set up the full system on a test bench in May.
  - Use the new calibration source to verify.
- Access to the region under repair limits us to installing only one monitor for now, in May and June.
- Commission in October?